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Mason et al.

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(54) **WAFER-BASED LIGHT SOURCE PARAMETER CONTROL**

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G03F 7/20 (2006.01)

(52) **U.S. Cl.**
CPC ***G03F 7/70625*** (2013.01); ***G03F 7/70041*** (2013.01); ***G03F 7/70575*** (2013.01)

(58) **Field of Classification Search**
CPC G03F 7/70625; G03F 7/70575; G03F 7/70041; G03F 7/70196; G03F 7/7006
USPC 355/53, 67–71; 250/492.1, 492.2
See application file for complete search history.

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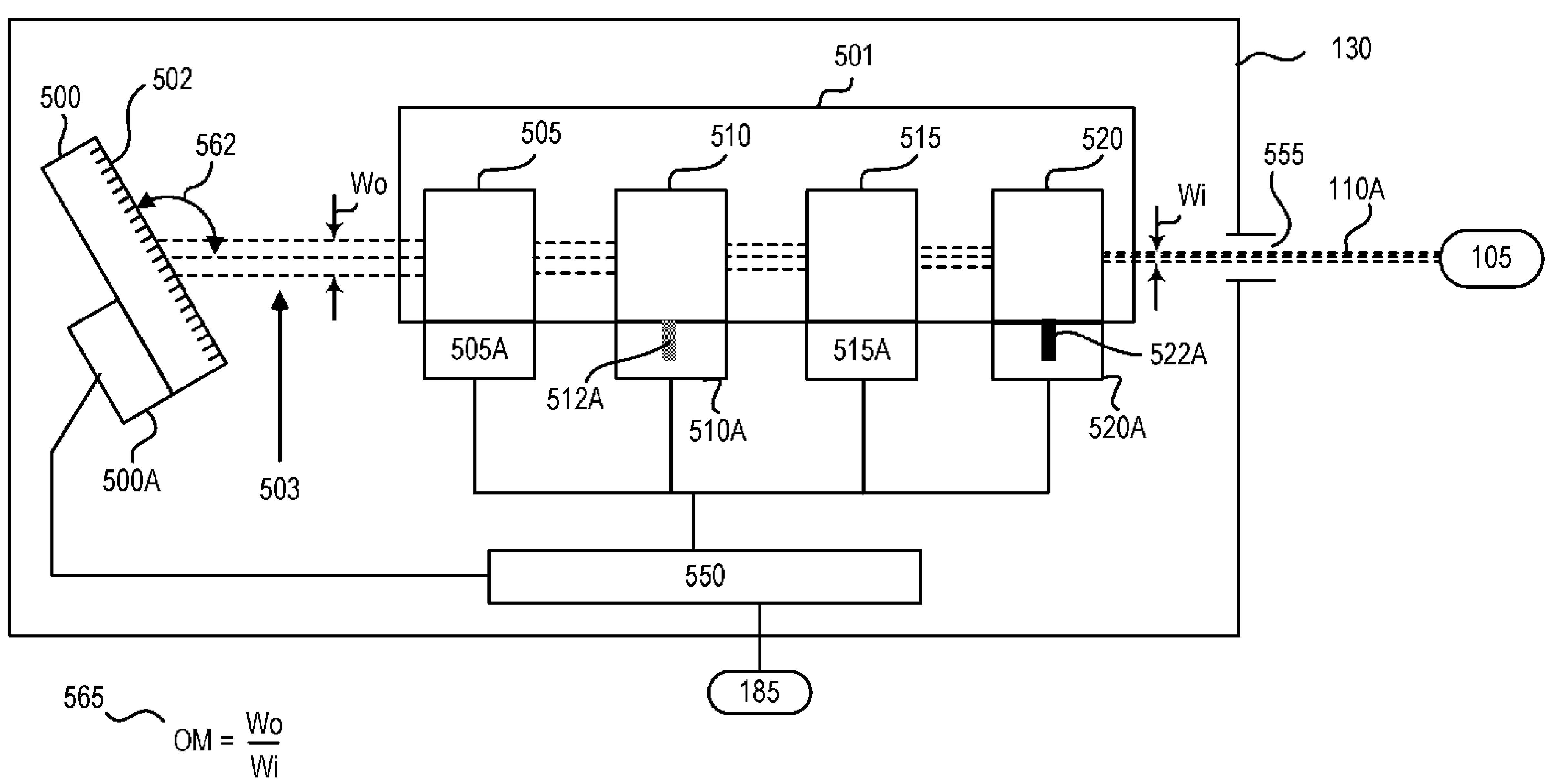
(57) **ABSTRACT**

A photolithography method includes producing, from an optical source, a pulsed light beam; and scanning the pulsed light beam across a substrate of a lithography exposure apparatus to expose the substrate with the pulsed light beam including exposing each sub-area of the substrate with the pulsed light beam. A sub-area is a portion of a total area of the substrate. For each sub-area of the substrate, a lithography performance parameter associated with the sub-area of the substrate is received; the received lithography performance parameter is analyzed, and, based on the analysis, a first spectral feature of the pulsed light beam is modified and a second spectral feature of the pulsed light beam is maintained.

20 Claims, 13 Drawing Sheets



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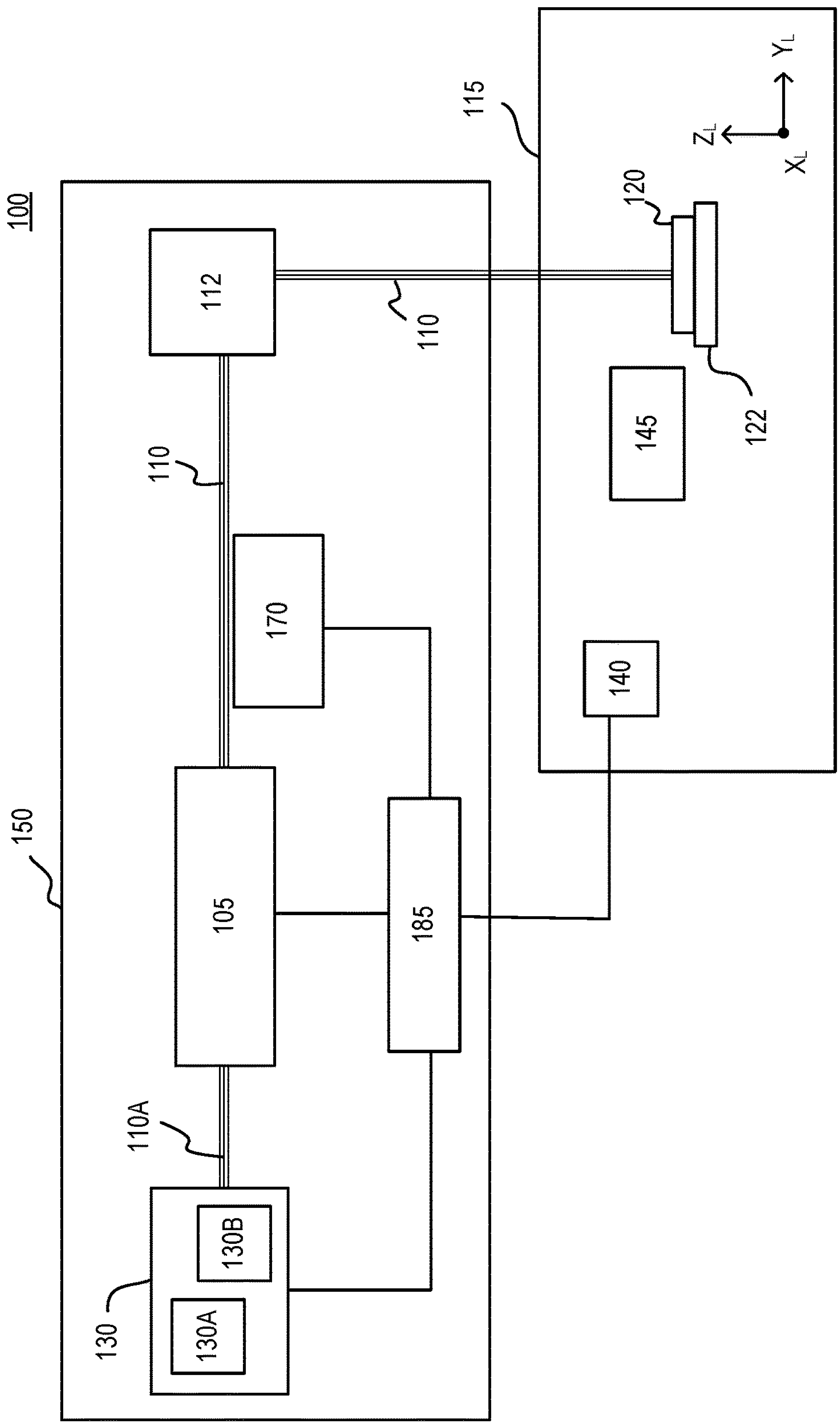

100
150
112
110
110
170
105
185
110A
130
130A
130B
115
120
122
145
140
Y_L
Z_L
X_L

Fig. 1

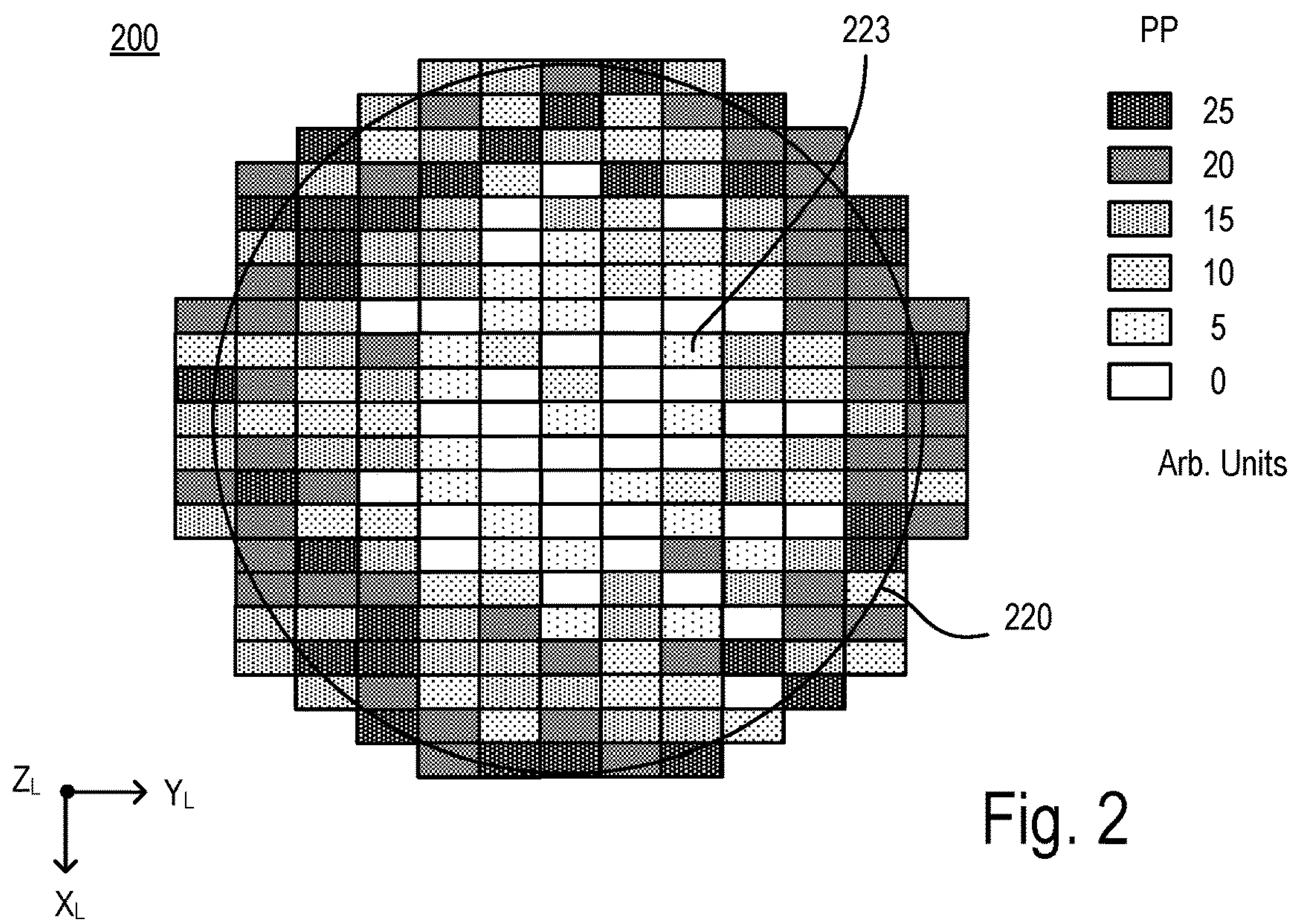

200
223
PP
25
20
15
10
5
0
Arb. Units
220
ZL
YL
XL

Fig. 2

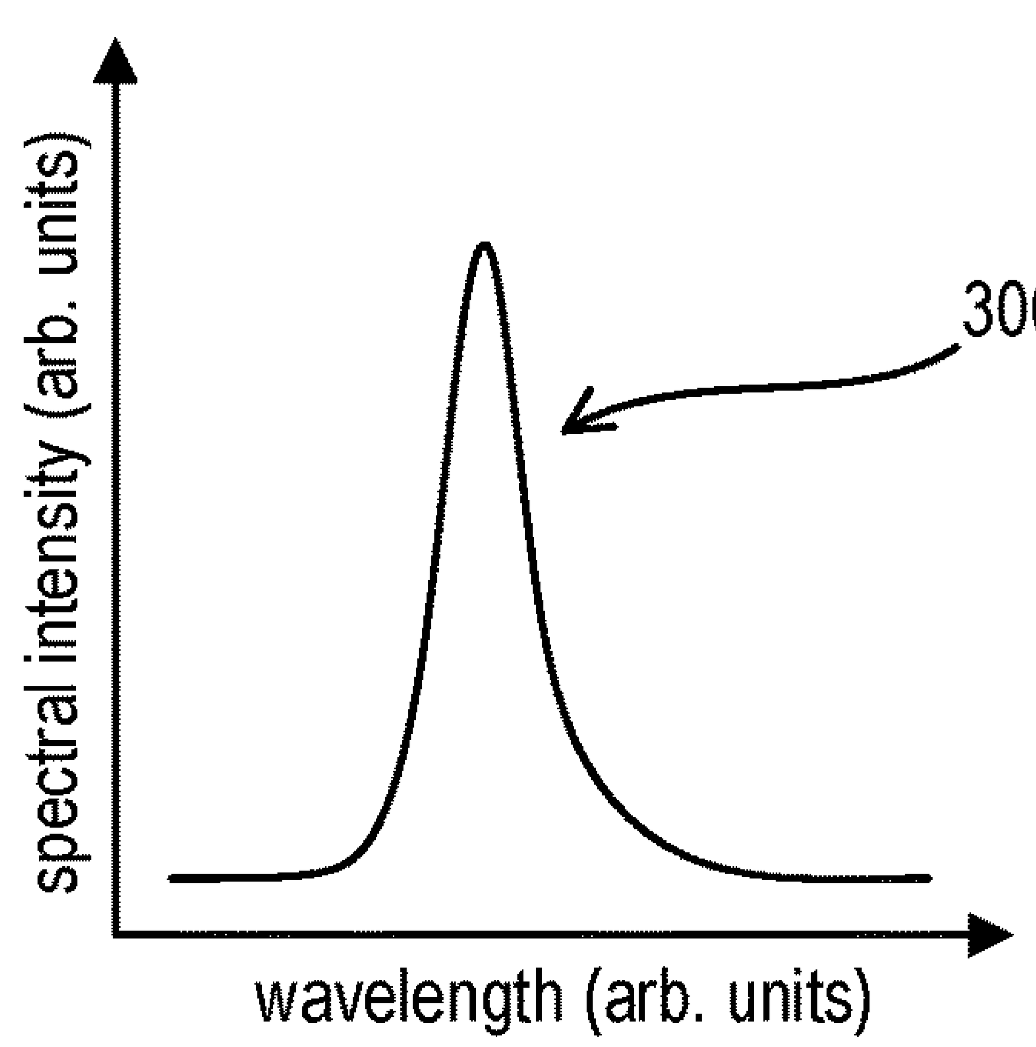

spectral intensity (arb. units)
300
wavelength (arb. units)

Fig. 3

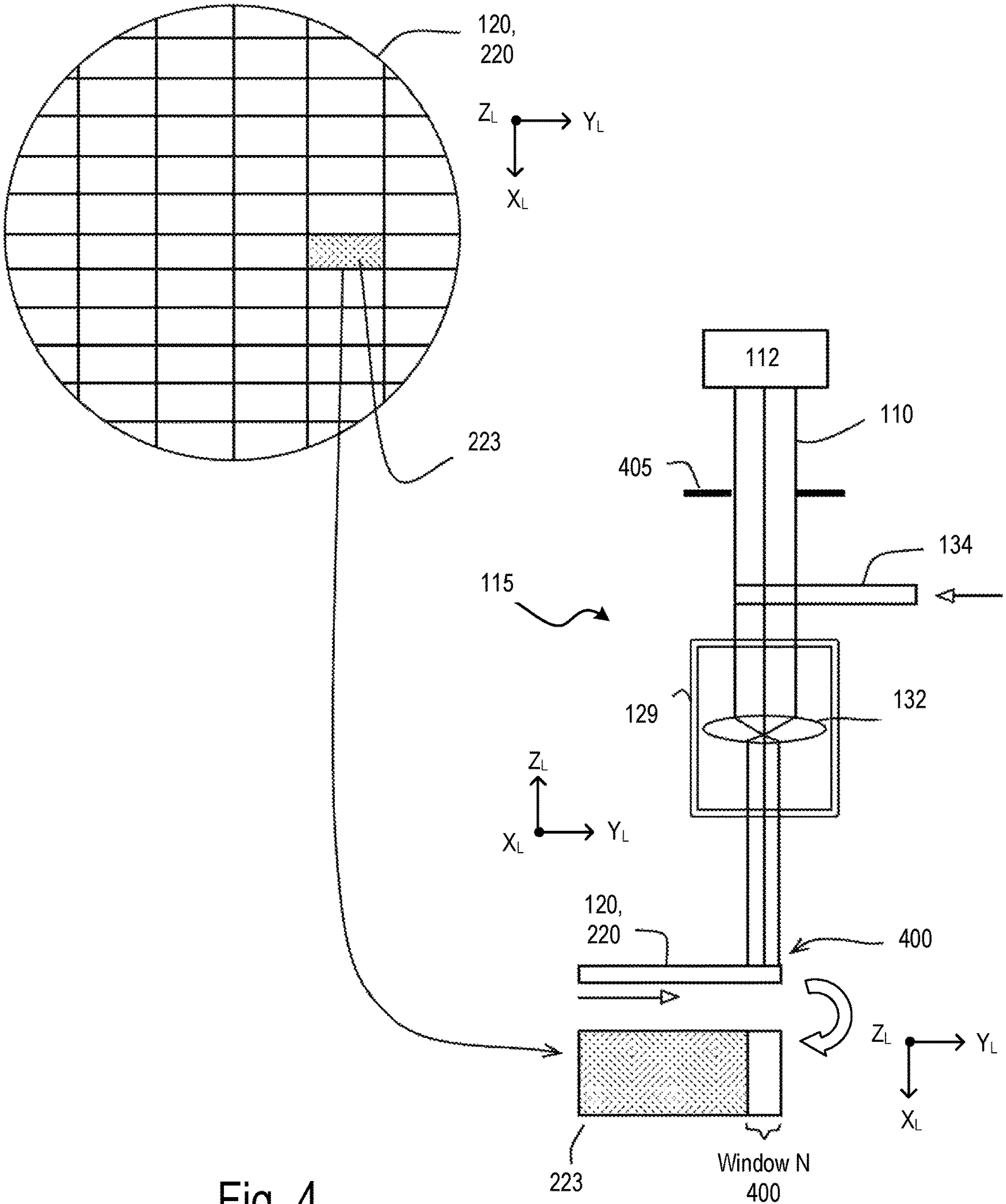

120,
220
Z_L
Y_L
X_L
223
112
110
405
134
115
129
132
Z_L
X_L
Y_L
120,
220
400
Z_L
Y_L
X_L
223
Window N
400

Fig. 4

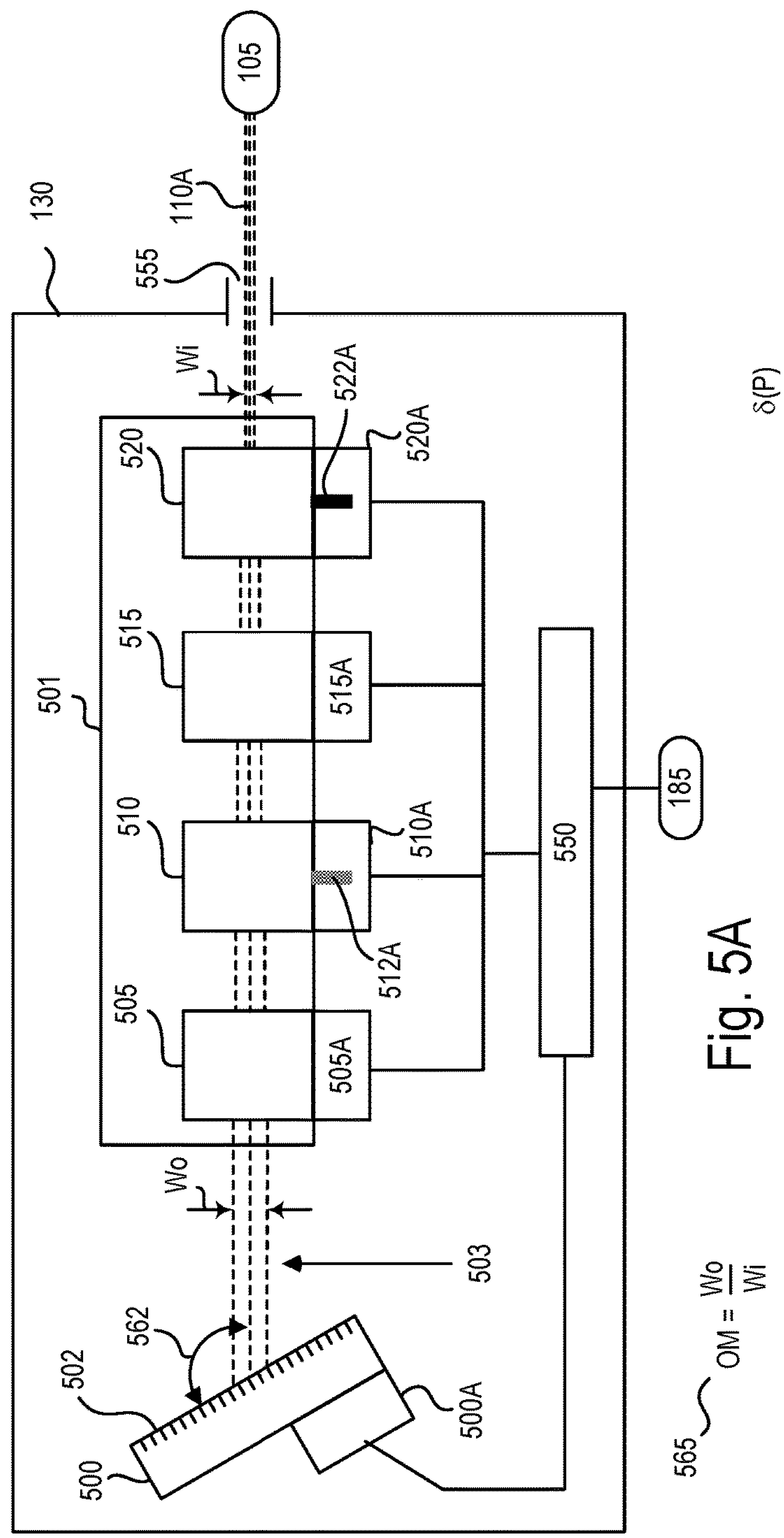

130
105
110A
555
Wi
522A
520
520A
501
515
515A
510
510A
512A
505
505A
550
185
Wo
503
562
502
500
500A
565
OM = Wo/Wi

Fig. 5A

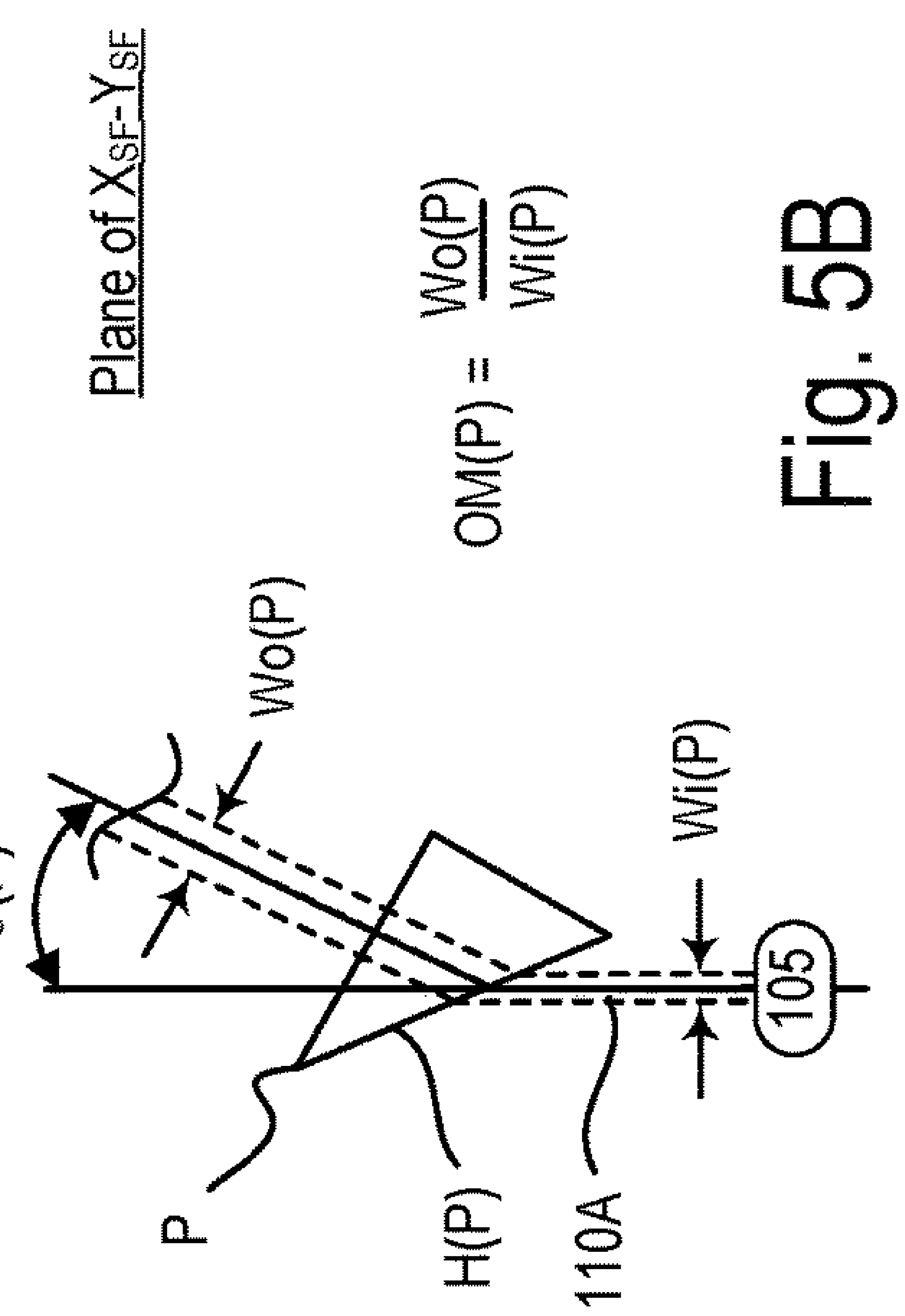

Plane of X_{SF}-Y_{SF}
OM(P) = Wo(P)/Wi(P)
Wo(P)
δ(P)
Wi(P)
105
P
H(P)
110A

Fig. 5B

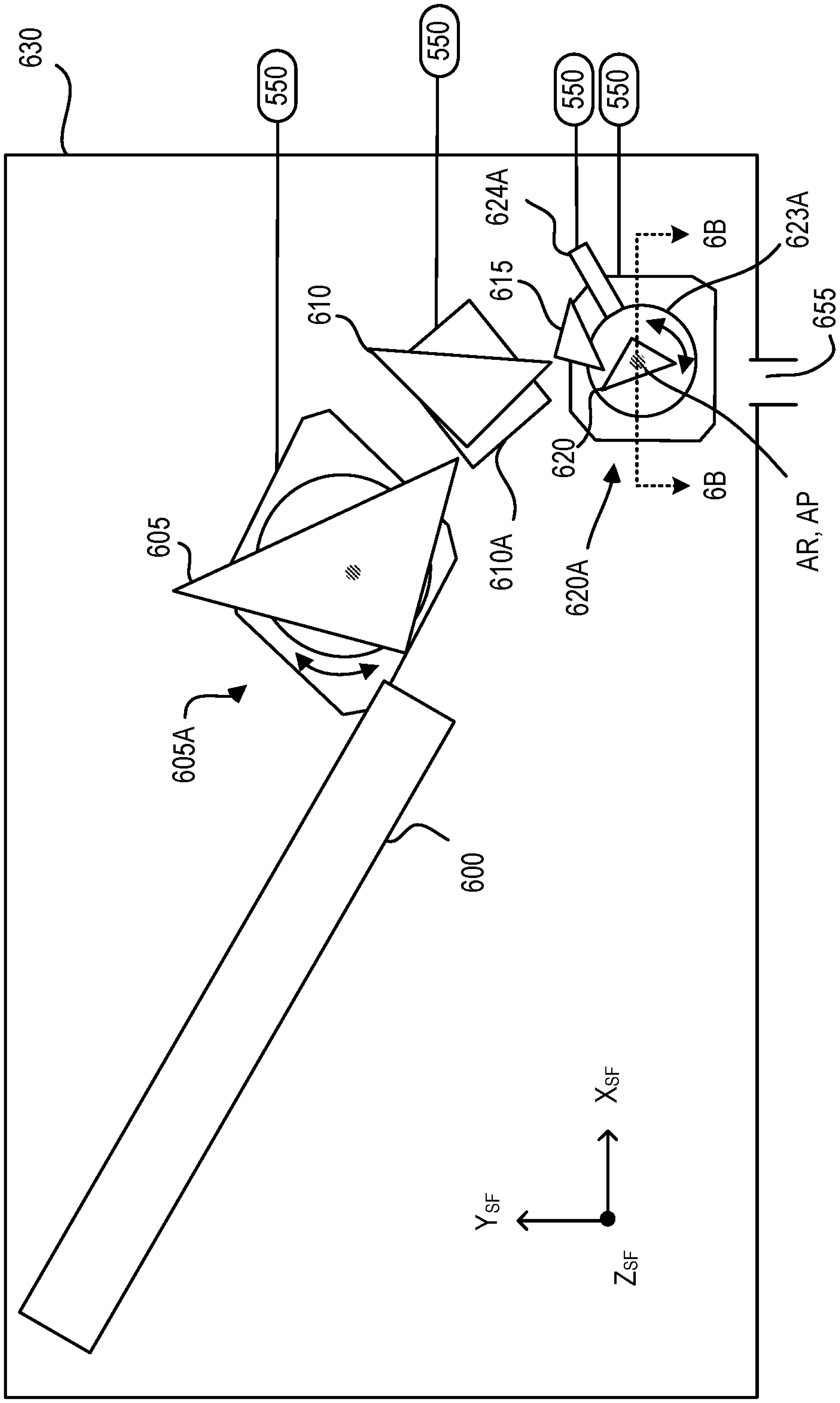

630
550
550
550
550
624A
623A
6B
615
610
655
620
6B
AR, AP
605
610A
620A
605A
600
X_{SF}
Y_{SF}
Z_{SF}

Fig. 6A

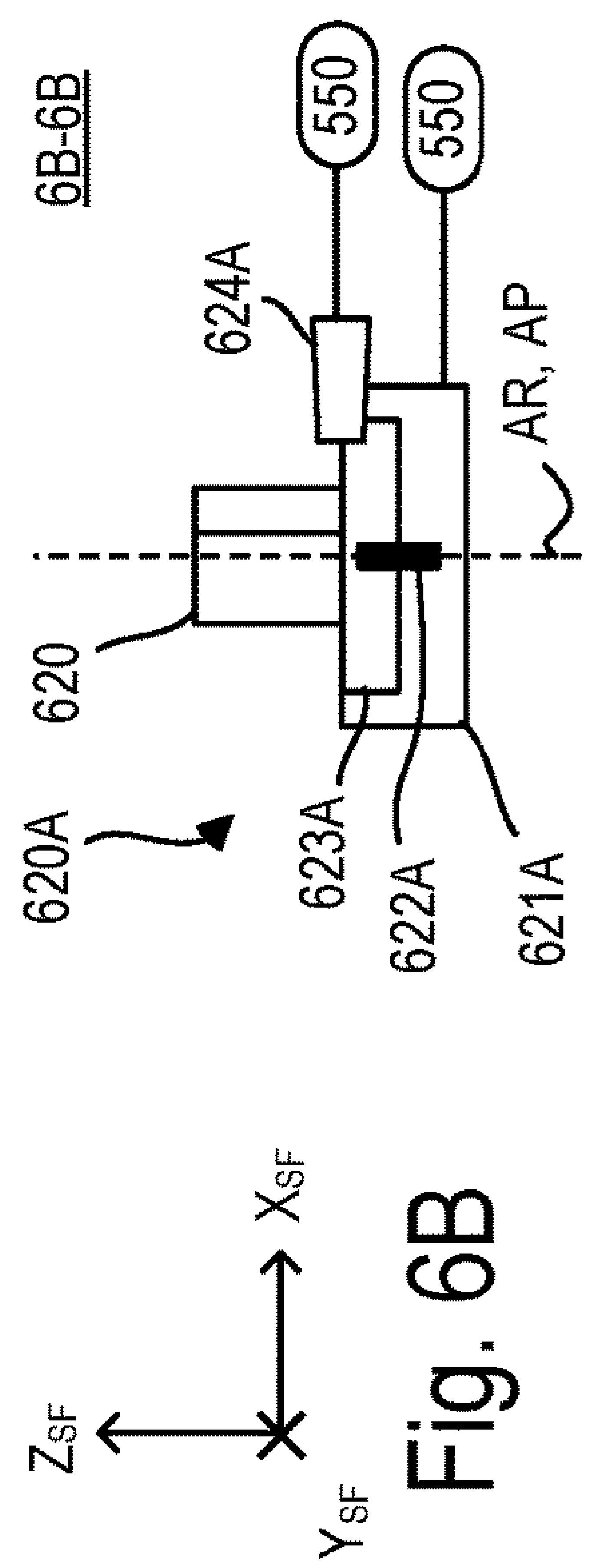

6B-6B
550
550
624A
AR, AP
620
620A
623A
622A
621A
Z_{SF}
X_{SF}
Y_{SF}

Fig. 6B

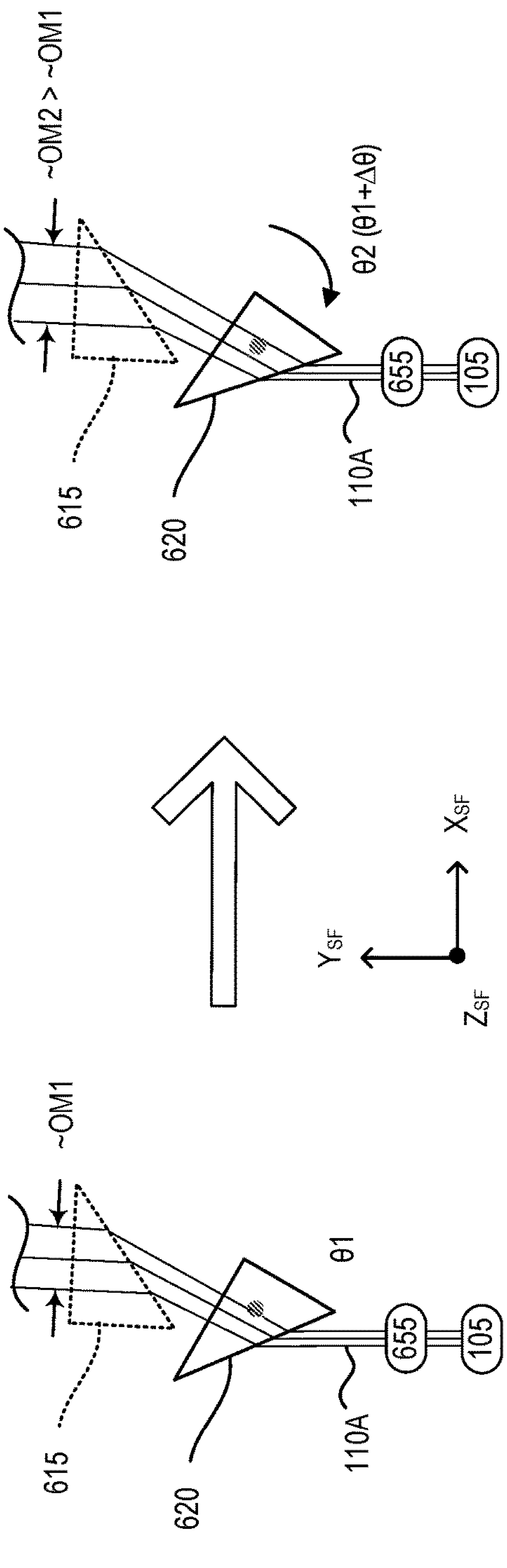

~OM2 > ~OM1
θ2 (θ1+Δθ)
655
105
615
620
110A
X_{SF}
Y_{SF}
Z_{SF}
~OM1
θ1
655
105
615
620
110A

Fig. 6C

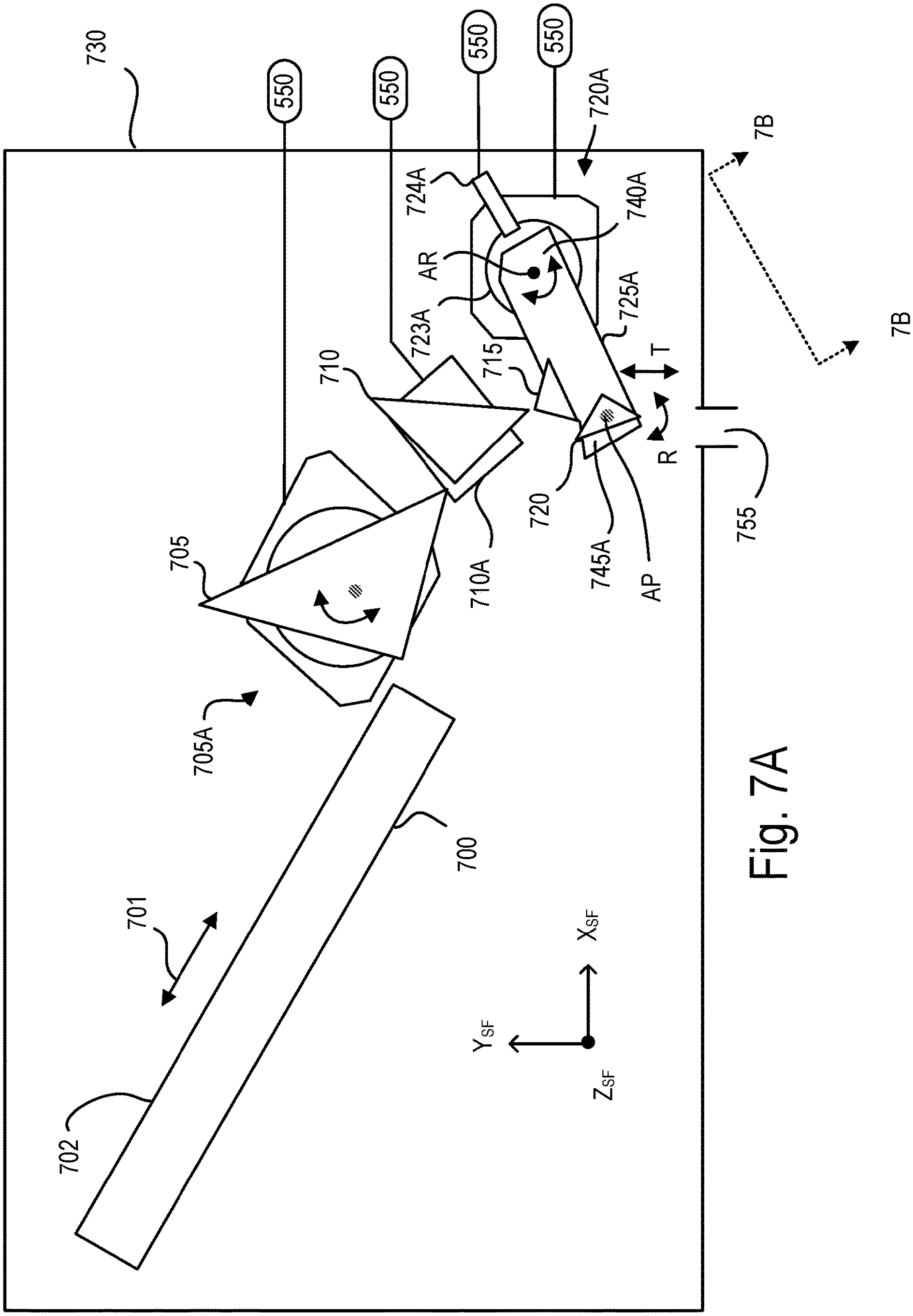

730
550
550
550
550
720A
7B
7B
724A
740A
AR
723A
725A
T
R
715
710
755
720
745A
AP
710A
705
705A
700
701
702
X_{SF}
Y_{SF}
Z_{SF}

Fig. 7A

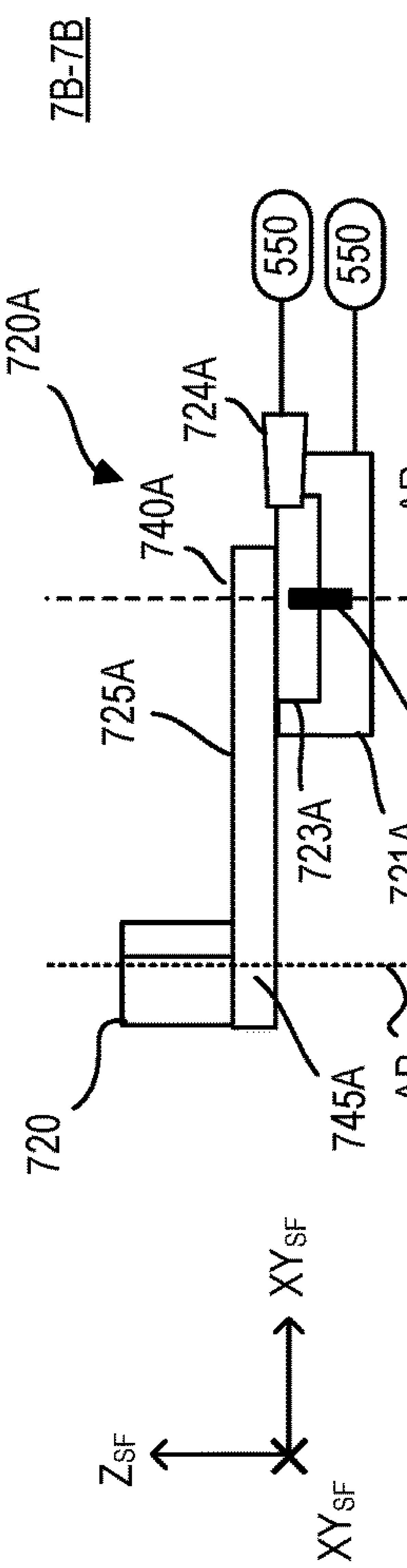

7B-7B
720A
724A
550
550
740A
AR
725A
722A
723A
721A
720
745A
AP
Z_{SF}
XY_{SF}
XY_{SF}

Fig. 7B

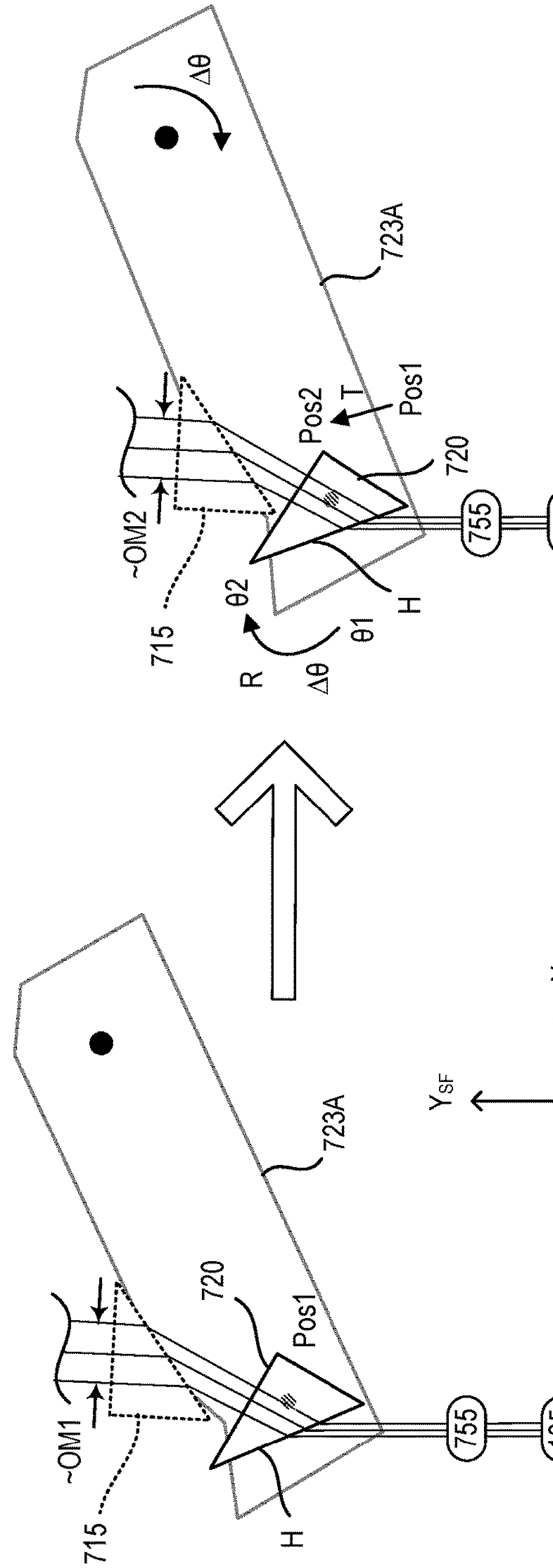

Δθ
723A
T
Pos2
Pos1
720
~OM2
755
105
θ2
H
715
R
θ1
Δθ
720
723A
Pos1
~OM1
755
105
715
H
X_{SF}
Y_{SF}
Z_{SF}

Fig. 7C

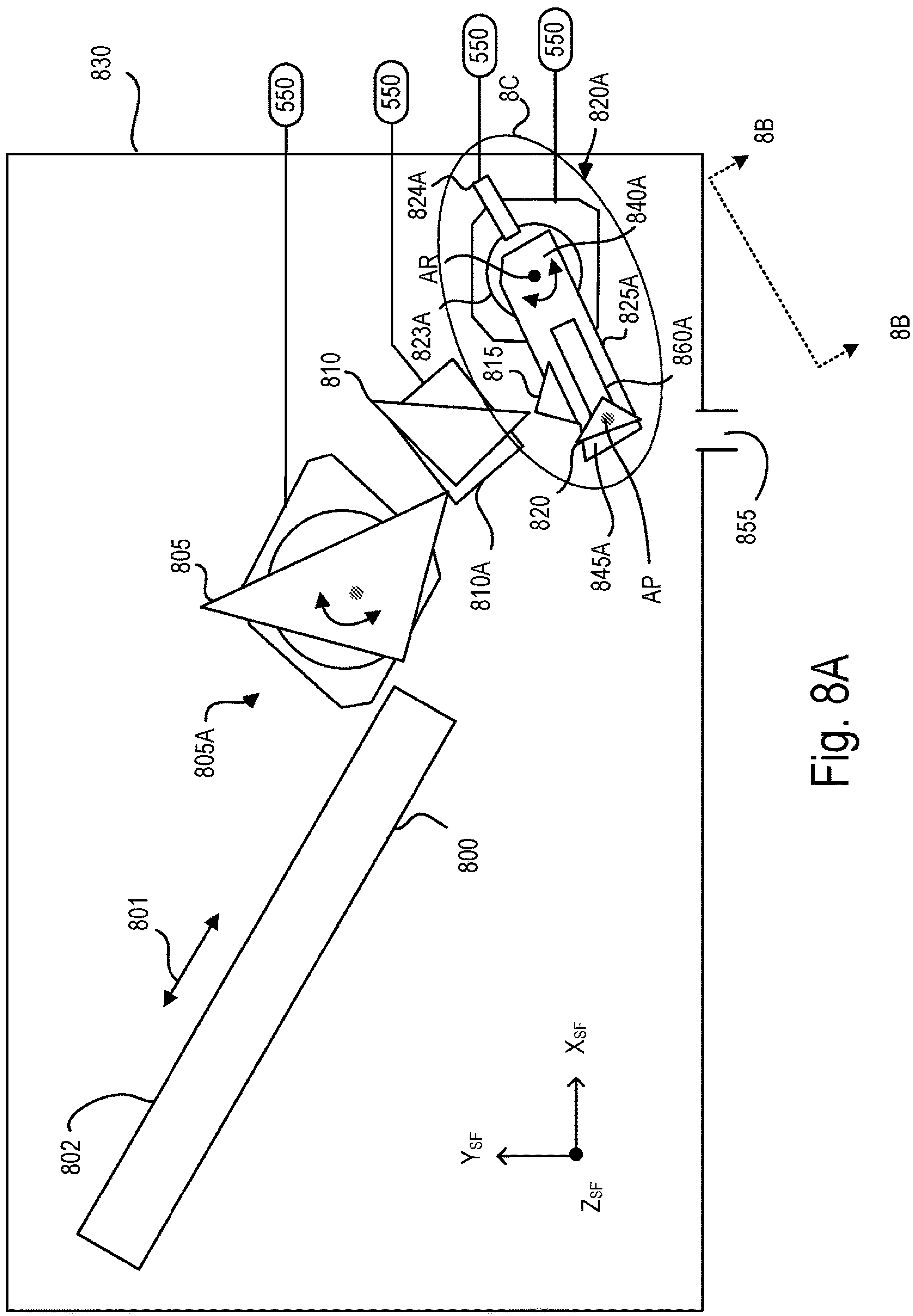

830
550
550
550
550
8C
820A
8B
824A
840A
AR
825A
8B
823A
860A
815
810
820
855
805
810A
845A
AP
805A
800
801
802
X_{SF}
Y_{SF}
Z_{SF}

Fig. 8A

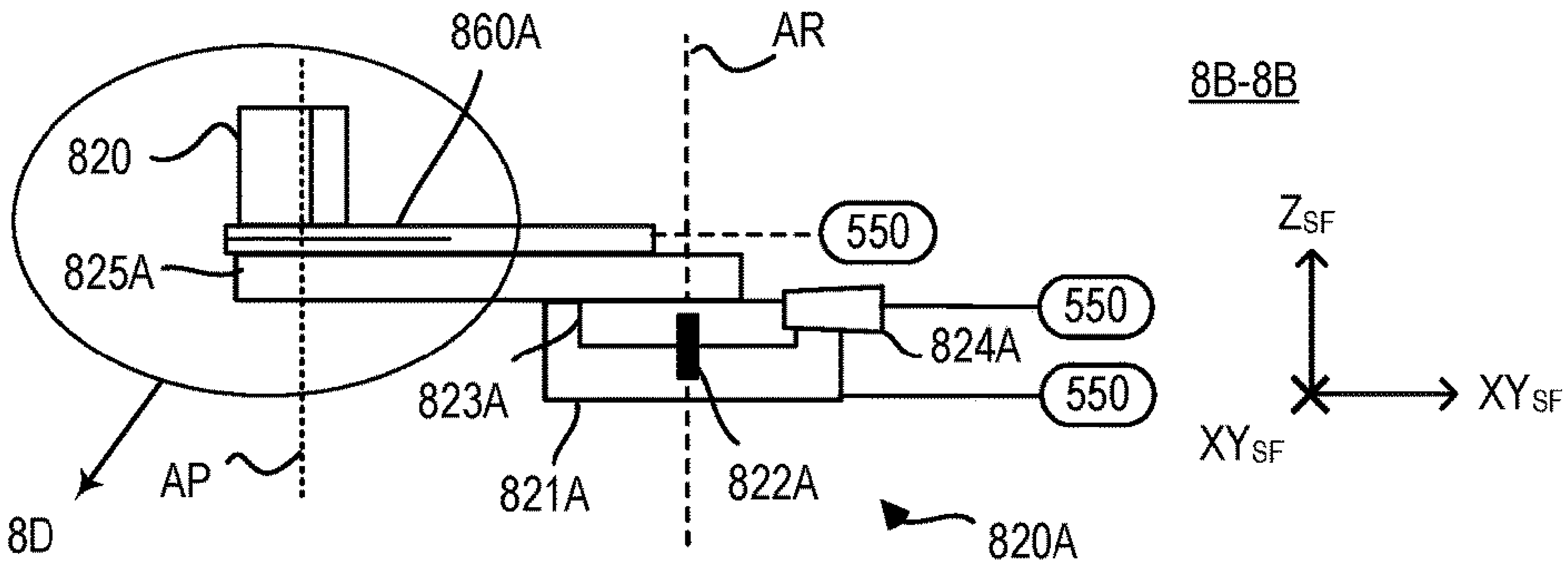


Fig. 8B

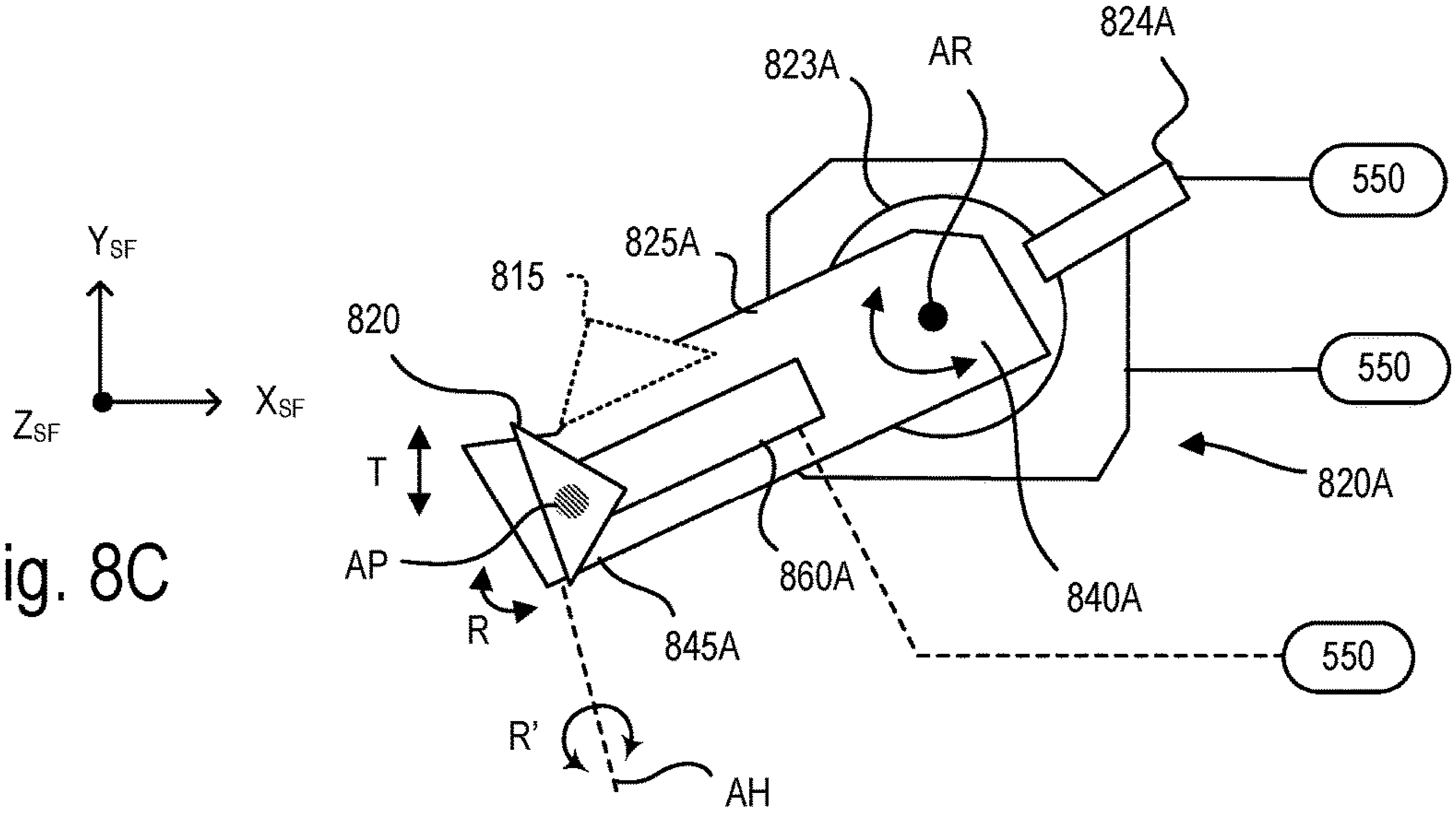


Fig. 8C

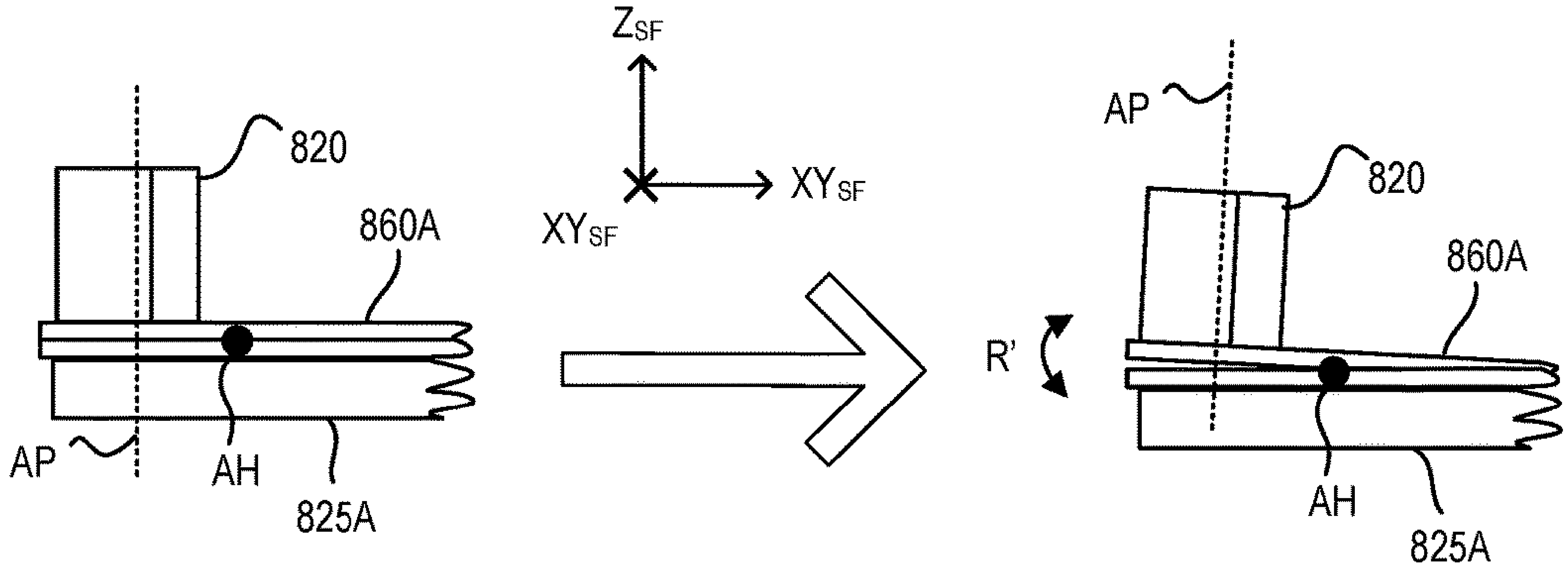


Fig. 8D

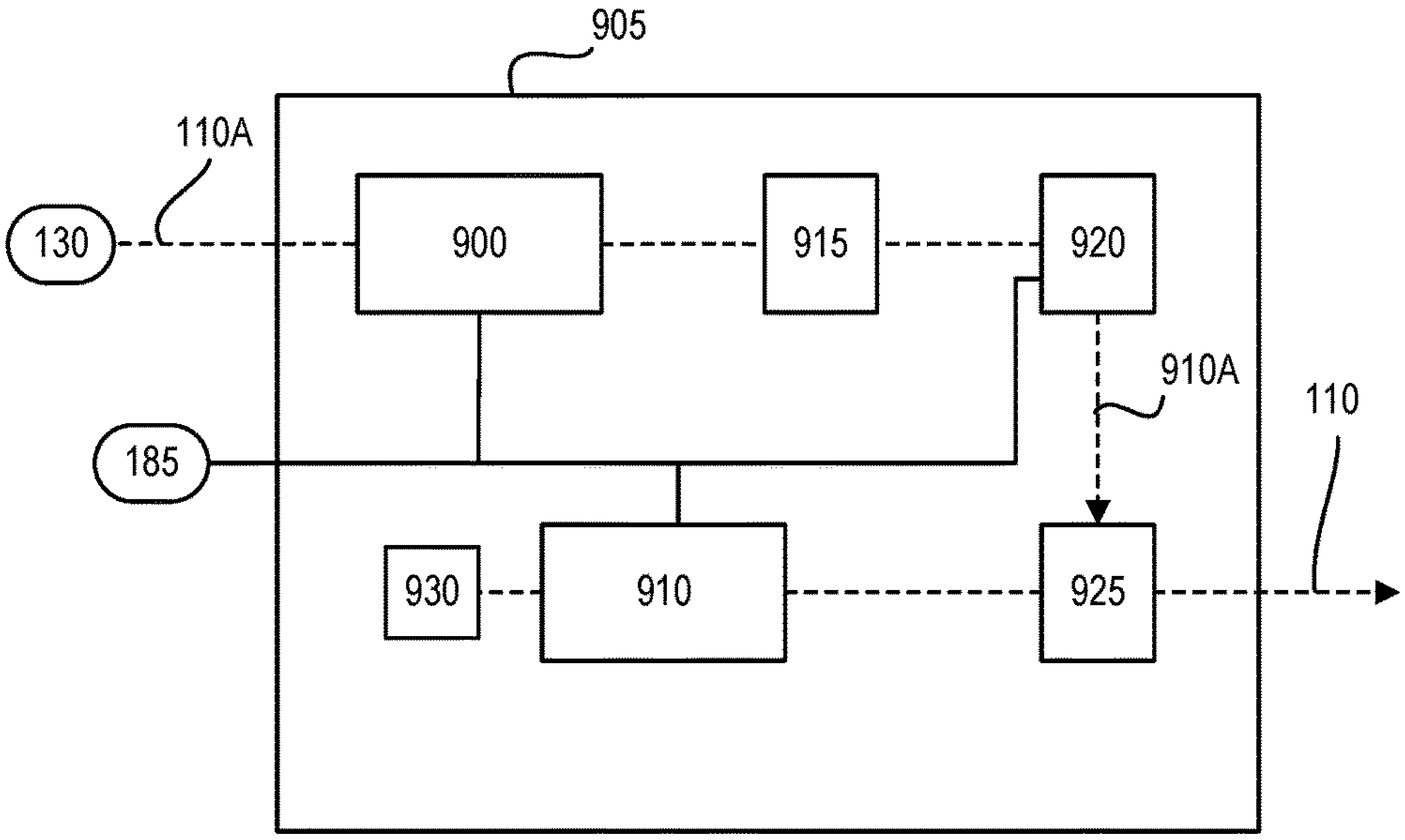

905
110A
130
900
915
920
910A
110
185
930
910
925

Fig. 9

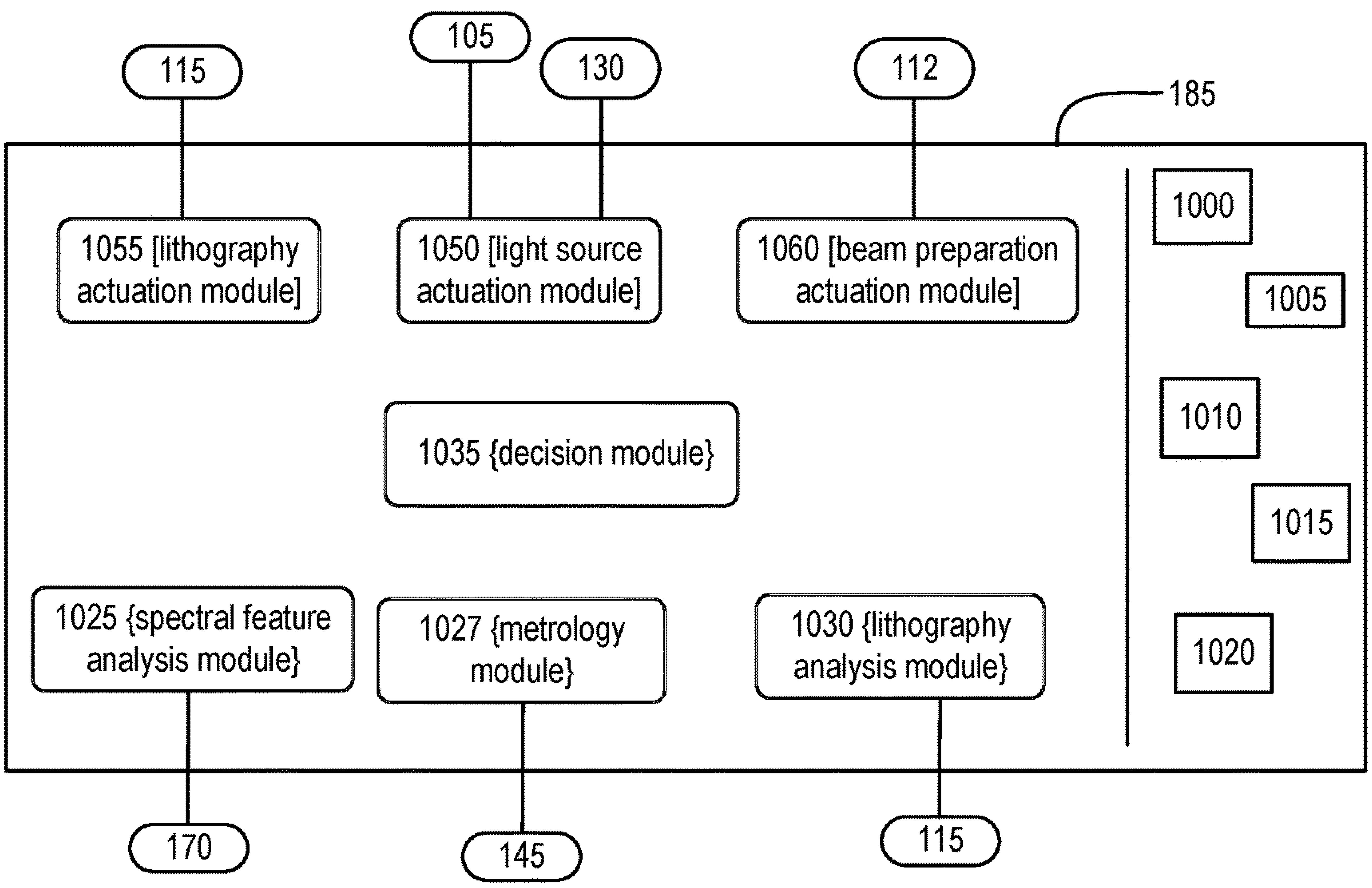
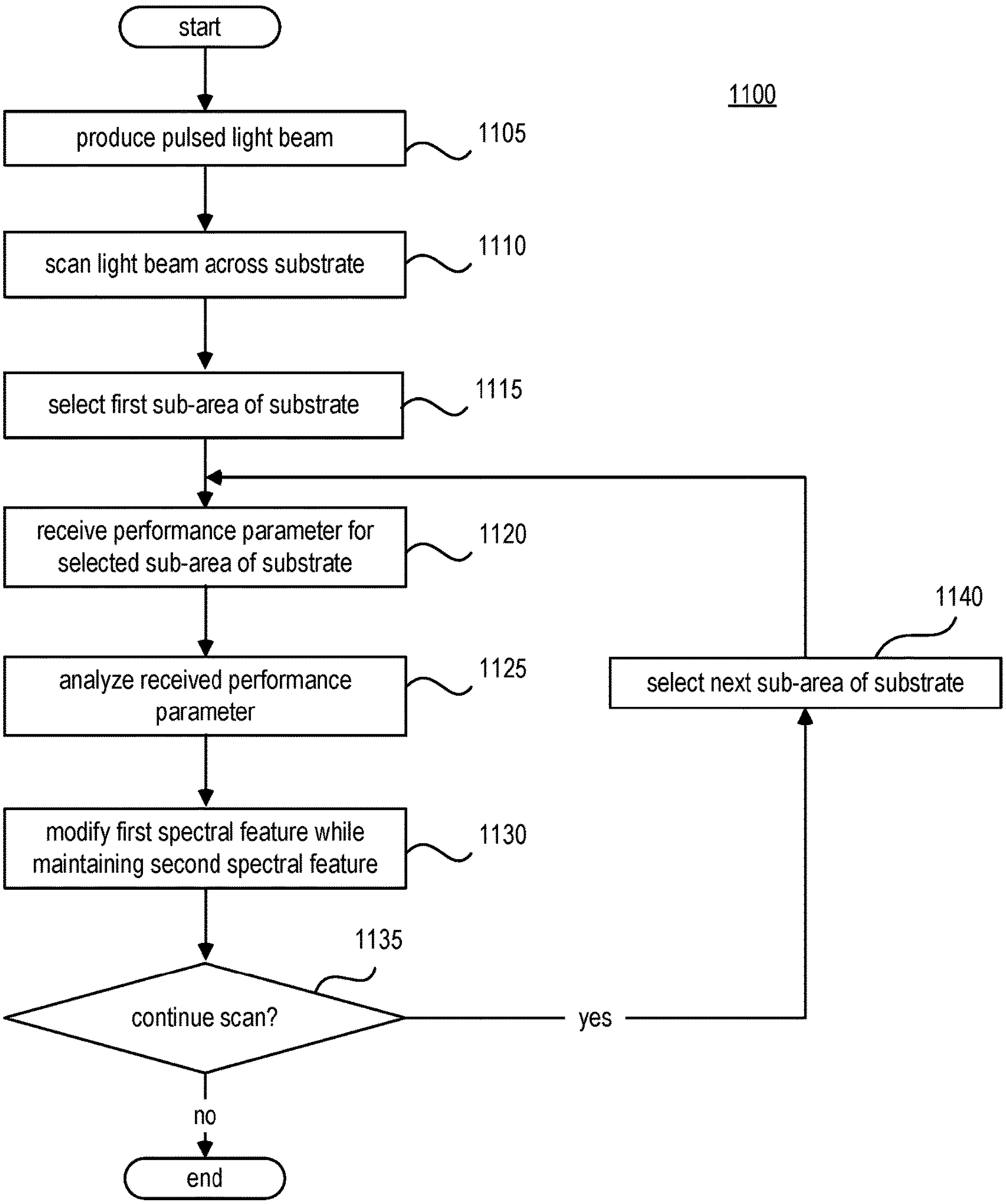

115
105
130
112
185
1055 [lithography actuation module]
1050 [light source actuation module]
1060 [beam preparation actuation module]
1000
1005
1035 {decision module}
1010
1015
1025 {spectral feature analysis module}
1027 {metrology module}
1030 {lithography analysis module}
1020
170
145
115

Fig. 10



start
1100
produce pulsed light beam
1105
scan light beam across substrate
1110
select first sub-area of substrate
1115
receive performance parameter for selected sub-area of substrate
1120
1140
analyze received performance parameter
1125
select next sub-area of substrate
modify first spectral feature while maintaining second spectral feature
1130
1135
continue scan?
yes
no
end

Fig. 11

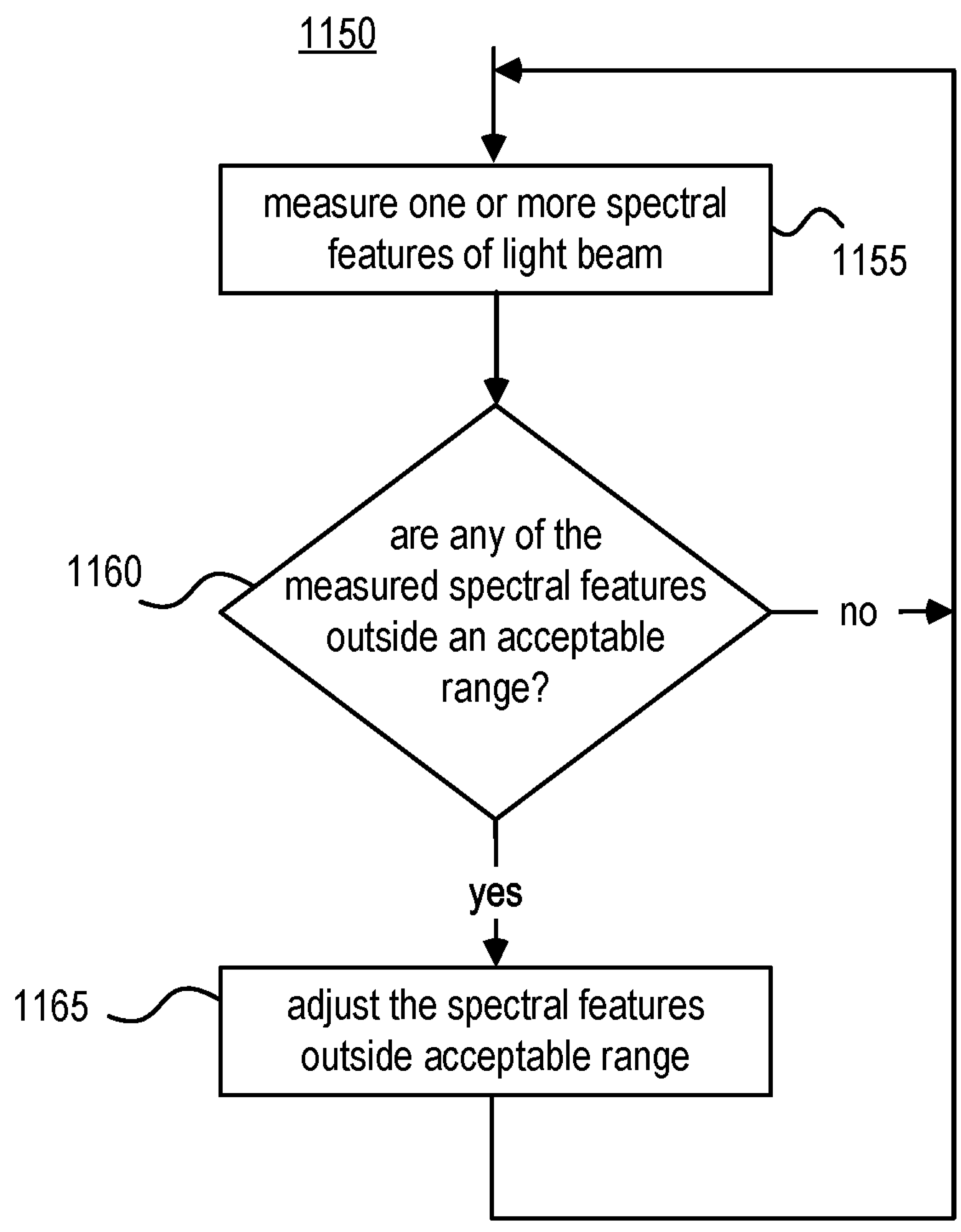

1150
measure one or more spectral features of light beam
1155
1160
are any of the measured spectral features outside an acceptable range?
no
yes
1165
adjust the spectral features outside acceptable range

Fig. 12

WAFER-BASED LIGHT SOURCE PARAMETER CONTROL

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 15/295,524, filed Oct. 17, 2016, which issued on Jun. 5, 2018 as U.S. Pat. No. 9,989,866, and titled WAFER-BASED LIGHT SOURCE PARAMETER CONTROL, which is related to U.S. application Ser. No. 15/295,280, filed on Oct. 17, 2016. Both applications are incorporated herein by reference in their entirety.

TECHNICAL FIELD

The disclosed subject matter relates to an apparatus for compensating for variations in lithography performance parameters during scanning of the wafer by adjusting a spectral feature of a pulsed light beam directed toward the wafer.

BACKGROUND

In semiconductor lithography (or photolithography), the fabrication of an integrated circuit (IC) requires a variety of physical and chemical processes performed on a semiconductor (for example, silicon) substrate (which is also referred to as a wafer). A photolithography exposure apparatus or scanner is a machine that applies a desired pattern onto a target portion of the substrate. The wafer is fixed to a stage so that the wafer generally extends along a plane defined by orthogonal X_L and Y_L directions of the scanner. The wafer is irradiated by a light beam, which has a wavelength in the deep ultraviolet (DUV) range. The light beam travels along an axial direction, which corresponds with the Z_L direction of the scanner. The Z_L direction of the scanner is orthogonal to the lateral X_L-Y_L plane. The light beam is passed through a beam delivery unit, filtered through a reticle (or mask), and then projected onto a prepared wafer. In this way, a chip design is patterned onto a photoresist that is then etched and cleaned, and then the process repeats.

SUMMARY

In some general aspects, a photolithography apparatus includes: an optical source configured to produce a pulsed light beam; a spectral feature selection system that optically interacts with the pulsed light beam; a scanning optical system configured to scan the pulsed light beam across a substrate positioned in a lithographic apparatus; a metrology apparatus configured to determine at least one lithography performance parameter at each sub-area of the substrate, in which a sub-area is a portion of a total area of the substrate; and a control system connected to the spectral feature selection system, the optical source, and the metrology apparatus. The control system is configured to, at each substrate sub-area: receive the determined lithography performance parameter; analyze the determined lithography performance parameter; and based on the analysis of the determined lithography performance parameter: modify a first spectral feature of the pulsed light beam by sending a first signal to the spectral feature selection system; and maintain a second spectral feature of the pulsed light beam

by sending a second signal to the spectral feature selection system while the first spectral feature of the pulsed light beam is being modified.

Implementations can include one or more of the following features. For example, each sub-area of the substrate can be an exposure field of the substrate or each sub-area can correspond to a single pulse of the light beam.

The spectral feature selection system can include a spectral feature actuation mechanism including an actuation system configured to cause one or more elements of the spectral feature actuation mechanism to be altered to thereby alter interaction with the pulsed light beam. The control system can be connected to the actuation system of the spectral feature actuation mechanism such that the first signal is sent to the actuation system of the spectral feature actuation mechanism and the second signal is sent to the actuation system of the spectral feature actuation mechanism.

The lithography performance parameter can be a physical property of the substrate. The control system can be configured to receive the determined value of the physical property of the substrate for each sub-area of the substrate. The physical property of the substrate can include one or more of a mean offset of a position of the substrate from a desired position and a stage vibration of the substrate. The physical property of the substrate can be a position of the substrate that varies from central sub-areas of the substrate to sub-areas at an edge of the substrate.

The spectral feature selection system can include a dispersive optical element and beam expander including at least three refractive optical elements. The pulsed light beam interacts with each of the dispersive optical element and the plurality of refractive optical elements. The spectral feature selection system can include an actuation system that includes a plurality of actuators, each of the actuators in the plurality causing one of the at least three refractive optical elements to rotate relative to the pulsed light beam. The at least three refractive optical elements can include a first refractive optical element that is farthest from the dispersive optical element, a second refractive optical element adjacent to the first refractive optical element, and a third refractive optical element adjacent to the second refractive optical element. The first refractive optical element can be associated with a first rapid actuator that includes a first rotation stage that rotates about a first rotation axis and includes a region that is mechanically linked to the first refractive optical element to rotate the first refractive optical element about the first rotation axis. The third refractive optical element can be associated with a second rapid actuator that includes a second rotation stage that rotates about a second rotation axis and includes a region that is mechanically linked to the third refractive optical element to rotate the third refractive optical element about the first rotation axis.

The rotation of the first refractive optical element can cause the second spectral feature of the pulsed light beam to be changed in a relatively coarse manner and the rotation of the third refractive optical element can cause the second spectral feature of the pulsed light beam to be changed in a relatively fine manner. The rotation of the second refractive optical element can cause the first spectral feature of the pulsed light beam to be changed in a relatively fine manner. The beam expander can include a fourth refractive optical element, and the rotation of the fourth refractive optical element can cause the first spectral feature of the pulsed light beam to be changed in a relatively coarse manner. The spectral feature selection system can include a reflective optical element between the beam expander and the dispersive optical element.

The control system can analyze the determined lithography performance parameter by determining whether the lithography performance parameter is outside an acceptable range; and the control system can modify the first spectral feature of the pulsed light beam if it is determined that the lithography performance parameter is outside an acceptable range by sending the signal to the spectral feature selection system.

The scanning optical system can be configured to move one or more of the pulsed light beam and the substrate relative to each other along a lateral plane such that the pulsed light beam interacts with each sub-area of the substrate. The lateral plane can be perpendicular to an axial direction along which the pulsed light beam is directed.

The optical source can include: a first gas discharge stage including a first gas discharge chamber housing an energy source and containing a gas mixture that includes a first gain medium; and a second gas discharge stage including a second gas discharge chamber housing an energy source and containing a gas mixture that includes a second gain medium. The first gas discharge stage is configured to generate a first pulsed light beam. The second gas discharge stage is configured to receive the first pulsed light beam and to amplify the first pulsed light beam to thereby produce the pulsed light beam from the optical source.

In other general aspects, a photolithography method includes: producing, from an optical source, a pulsed light beam; and scanning the pulsed light beam across a substrate of a lithography exposure apparatus to expose the substrate with the pulsed light beam including exposing each sub-area of the substrate with the pulsed light beam, wherein a sub-area is a portion of a total area of the substrate. The method includes, for each sub-area of the substrate: receiving a lithography performance parameter associated with the sub-area of the substrate; analyzing the received lithography performance parameter; and based on the analysis, modifying at least a first spectral feature of the pulsed light beam and maintaining at least a second spectral feature of the pulsed light beam.

Implementations can include one or more of the following features. For example, the pulsed light beam can be produced by directing the pulsed light beam through a spectral feature selection system. The method can include selecting the first spectral feature of the pulsed light beam by selectively reflecting the pulsed light beam from a diffractive surface of the spectral feature selection system.

The sub-area of the substrate can be an exposure field of the substrate or it can correspond to a single pulse of the light beam.

The lithography performance parameter can be received at each sub-area of the substrate by receiving the lithography performance parameter at each sub-area of the substrate during scanning of the pulsed light beam across the substrate.

The lithography performance parameter can be received at the sub-area by receiving one or more of an error on the physical property of the substrate, a contrast of a feature formed on the substrate, a critical dimension at a substrate area exposed to the pulsed light beam, the placement (X, Y location relative to desired/target location) of the feature formed on the substrate relative to a target or relative to an underlying feature (that is, an overlay), a photoresist profile, a side-wall angle, and a change in position of the substrate.

The lithography performance parameter at the sub-area can be received by receiving one or more of a mean offset of a position of the substrate from a desired position and a stage vibration of the substrate. The lithography performance parameter at the sub-area can be received by receiving a position of the substrate that varies from central sub-areas of the substrate to sub-areas at an edge of the substrate.

The lithography performance parameter at each sub-area of the substrate can be received by receiving the lithography performance parameter at each sub-area of the substrate prior to scanning the pulsed light beam across the substrate.

The first spectral feature can be modified by modifying the wavelength of the pulsed light beam, and the second spectral feature can be maintained by maintaining the bandwidth of the pulsed light beam to within a range of bandwidths.

The bandwidth of the pulsed light beam can be maintained to within the range of bandwidths by maintaining the bandwidth of the pulsed light beam to within ±10 femtometers (fm) or within ±1 fm.

The first spectral feature of the pulsed light beam can be modified by rotating a first prism system through which the pulsed light beam passes; and the second spectral feature of the pulsed light beam can be maintained by rotating a second prism system through which the pulsed light beam passes. The first prism system and the second prism system can be components within a spectral feature selection system. The first prism system through which the pulsed light beam passes can be rotated by rotating two prisms through which the pulsed light beam passes; and the second prism system through which the pulsed light beam passes can be rotated by rotating at least two other prisms through which the pulsed light beam passes. The two prisms of the first prism system can be rotated by actuating one of the prisms of the first prism system in actuation steps that are larger than the actuation steps for actuation of the other of the prisms of the first prism system. The two other prisms of the second prism system can be rotated by actuating one of the prisms of the second prism system in actuation steps that are larger than the actuation steps for actuation of the other of the prisms of the second prism system.

The first spectral feature of the pulsed light beam can be modified by rotating a mirror on which the pulsed light beam reflects; and the second spectral feature of the pulsed light beam can be maintained by rotating a prism system through which the pulsed light beam passes. The mirror and the prism system are components within a spectral feature selection system.

The method can also include: at least at each sub-area of the substrate, estimating the first spectral feature of the pulsed light beam produced from the optical source; determining whether the estimated first spectral feature is within an acceptable range; and, if it is determined that the estimated first spectral feature is not within the acceptable range, then modifying the first spectral feature of the pulsed light beam.

The method can include: at least at each sub-area of the substrate, estimating the second spectral feature of the pulsed light beam produced from the optical source; determining whether the estimated second spectral feature is within an acceptable range; and, if it is determined that the estimated second spectral feature is not within the acceptable range, then modifying the second spectral feature of the pulsed light beam.

The second spectral feature of the pulsed light beam can be maintained by adjusting the second spectral feature to compensate for changes of the second spectral feature due to the modification of the first spectral feature of the pulsed light beam; and the second spectral feature of the pulsed light beam can be adjusted simultaneously with modifying the first spectral feature of the pulsed light beam.

The received lithography performance parameter can be analyzed by determining whether a physical property of the substrate is outside an acceptable range based on the lithography performance parameter.

The first spectral feature of the pulsed light beam can be modified to thereby cause a modification to a first condition of the pulsed light beam at the substrate and the second spectral feature of the pulsed light beam can be maintained to thereby cause a second condition of the pulsed light beam at the substrate to be maintained at a particular level.

The pulsed light beam can be produced from the optical source by: generating a first pulsed light beam from a first gas discharge stage including selecting the first spectral feature of the pulsed light beam; directing the first pulsed light beam to a second gas discharge stage; and amplifying the first pulsed light beam in the second gas discharge stage to thereby produce the pulsed light beam from the optical source.

The at least the first spectral feature of the pulsed light beam can be modified and the at least the second spectral feature of the pulsed light beam can be maintained by: directing the pulsed light beam through a plurality of prisms toward a diffractive optical element so that the pulsed light beam retro reflects off the diffractive optical element and back through the plurality of prisms; and simultaneously rotating the at least two right-angled prisms so that an angle of incidence of the pulsed light beam on the diffractive optical element is changed but the total magnification of the pulsed light beam on the diffractive optical element is unchanged.

In other general aspects, a photolithography method includes: producing, from an optical source, a pulsed light beam; receiving a recipe that correlates edge roll off of a substrate to each sub-area of the substrate, wherein a sub-area is a portion of a total area of the substrate; scanning the pulsed light beam across the substrate of a lithography exposure apparatus to expose the substrate with the pulsed light beam including exposing each sub-area of the substrate with the pulsed light beam; modifying at least a wavelength of the pulsed light beam so as to adjust the focal position at the substrate to compensate for edge roll off and based on the sub-area being exposed; and maintaining at least a bandwidth of the pulsed light beam while the wavelength of the pulsed light beam is being modified to adjust the focal position at the substrate and compensate for edge roll off for the sub-area being exposed.

DESCRIPTION OF DRAWINGS

FIG. **1** is a block diagram of a photolithography system producing a pulsed light beam that is directed to a photolithography exposure apparatus;

FIG. **2** is a schematic drawing depicting a map of a wafer that is imaged within the photolithography exposure apparatus of FIG. **1**, the map showing the sub-areas of the wafer;

FIG. **3** is a graph of an exemplary optical spectrum of the pulsed light beam produced by the photolithography system of FIG. **1**;

FIG. **4** is a block diagram of an exemplary photolithography exposure apparatus that can be used in the photolithography system of FIG. **1**;

FIG. **5**A is a block diagram of an exemplary spectral feature selection apparatus that can be used in the photolithography system of FIG. **1**;

FIG. **5**B is a block diagram of an exemplary prism within the spectral feature selection apparatus of FIG. **5**A, and showing a beam magnification and beam refraction angle through the prism;

FIG. **6**A is a block diagram of exemplary spectral feature selection apparatus that includes a rapid actuator associated with at least one of the prisms and can be used in the photolithography system of FIG. **1**;

FIG. **6**B is a view taken along the **6**B-**6**B section of one of the prisms of the apparatus of FIG. **6**A;

FIG. **6**C is a view along the Z_{SF} direction of the prism of FIG. **6**B showing rotation of the prism;

FIG. **7**A is a block diagram of exemplary spectral feature selection apparatus that includes a rapid actuator associated with at least one of the prisms and can be used in the photolithography system of FIG. **1**;

FIG. **7**B is a view taken along the **7**B-**7**B section of one of the prisms of the apparatus of FIG. **7**A;

FIG. **7**C is a view along the Z_{SF} direction of the prism of FIG. **7**B showing rotation of the prism;

FIG. **8**A is a block diagram of exemplary spectral feature selection apparatus that includes a rapid actuator associated with at least one of the prisms and can be used in the photolithography system of FIG. **1**;

FIG. **8**B is a view taken along the **8**B-**8**B section of one of the prisms of the apparatus of FIG. **8**A;

FIG. **8**C is a view along the Z_{SF} direction of the prism of FIG. **8**B showing rotation of the prism;

FIG. **8**D is a close-up view taken along the **8**B-**8**B section shown in FIG. **8**B;

FIG. **9** is a block diagram of an exemplary optical source that can be used in the photolithography system of FIG. **1**;

FIG. **10** is a block diagram of an exemplary control system that can be used in the photolithography system of FIG. **1**;

FIG. **11** is a flow chart of an exemplary procedure performed by the photolithography system of FIG. **1** to rapidly and independently control at least two spectral features of the pulsed light beam to compensate for a variation in characteristics at the wafer in each sub-area of the wafer; and

FIG. **12** is a flow chart of an exemplary procedure performed by the photolithography system of FIG. **1** to control one or more spectral features of the pulsed light beam.

DESCRIPTION

Referring to FIG. **1**, a photolithography system **100** includes an illumination system **150** that produces a pulsed light beam **110** having a wavelength that is nominally at a center wavelength and is directed to a photolithography exposure apparatus or scanner **115**. The pulsed light beam **110** is used to pattern microelectronic features on a substrate or wafer **120** that is mounted to a stage **122** in the scanner **115**. These microelectronic features patterned on the wafer **120** are limited in size by the critical dimension (CD).

As the pulsed light beam **110** is being scanned across the wafer **120**, the scanner **115** or a control system **185** periodically requests changes to a spectral feature (such as the wavelength or the bandwidth) of the light beam **110** to compensate for variations in lithography performance parameters happening at the wafer **120**. For example, one or more lithography performance parameters can vary with each sub-area of the wafer **120** that is being scanned by the pulsed light beam **110**. A sub-area of the wafer **120** is an area of the wafer **120** that is a fraction of the total area of the wafer that is being scanned and can be an exposure field of the wafer or an area of the wafer **120** that interacts with a single pulse of the light beam **110**. The sub-area of the wafer **120** can be that location at which the wafer **120** is being exposed to the light beam **110** at any one particular time.

Such lithography performance parameters at the wafer **120** can be considered to be characteristics associated with the wafer **120** or with the light beam **110** interacting with the wafer **120**. For example, chromatic aberration due to the bandwidth of the light beam **110**, pressure, temperature, wafer topography or surface shape, change in position of the wafer **120**, and error in the focal plane of the light beam **110** are lithography performance parameters that can fluctuate unexpectedly during the scanning across the wafer **120**.

The pressure and temperature parameters are, respectively, the pressure and temperature in the environment near the wafer **120** within the scanner **115**. Variations in pressure and temperature induce effective changes in the wavelength of the light beam **110**, and thus induce changes to the focal plane of the light beam **110**.

In a specific example, most projection lenses (used in the path of the light beam **110** as it travels to the wafer **120**) have chromatic aberration, which produces an imaging error on the wafer **120** if there is a wavelength error in the light beam **110**. One error caused by chromatic aberration is focus error and other errors tend to be much smaller. For example, if the wavelength of the light beam **110** is off of the target wavelength, the image on the wafer **120** will have a significant focal plane error. Thus, it is desirable to be able to change the wavelength of the light beam **110** as it is being scanned across the wafer **120** to compensate for these focal plane errors that are caused by the chromatic aberration.

As another example, a lithography performance parameter that can vary from one sub-area to another of the wafer **120** is the position of the wafer **120** along the Z_L direction. The position of the wafer **120** includes an offset (such as a mean offset), which is a fixed offset from a desired position, and also includes a stage vibration or oscillation, which is an oscillation about that fixed offset in position. The stage vibration along the Z_L direction can be characterized by a moving standard deviation (MSD) value that is derived from a stage error signal. Higher values of stage vibration blur the image and thus cause non-uniformity in the CD. The mean offset along the Z_L direction is characterized by a moving average (MA) value. The topography of the wafer **120** can contribute to or cause an unwanted effect called edge roll off in which the wafer exhibits a different surface geometry at the sub-areas along its edge (and farthest from its central sub-areas). In particular, the wafer **120** best focus position may have a much different value along the edge or near the edge of the wafer **120** than it does near the center of the wafer **120** (such an effect can be seen in FIG. **2**, as discussed below).

Referring to FIG. **2**, an exemplary map **200** of a wafer **220** is shown in which a lithography performance parameter PP is plotted for each sub-area (for example, each exposure field **223**) of the wafer **220**. Higher values of the PP are darker and lower values of the PP are lighter. The map **200** of the wafer **220** shows how the PP varies across exposure fields **223** of the wafer **220**. The exposure field **223** of the wafer **220** is the area of the wafer **220** that is exposed in one scan of an exposure slit or window within the scanner **115**.

The photolithography system **100** and associated method described herein is designed to enable modifications to a first spectral feature such as the wavelength of the light beam **110** as it is being scanned across the wafer **120** and upon instruction from the scanner **115** to compensate for variations in these performance parameters at the wafer **120**. The modification to the first spectral feature of the light beam **110** is implemented by and under control of a spectral feature selection apparatus **130** that is configured to interact with a pulsed light beam **110**A that is a seed beam for forming the light beam **110** output from the illumination system **150**. Because of the design of the spectral feature selection apparatus **130**, other spectral features of the light beam **110** may be coupled to the first spectral feature such that by changing the first spectral feature, a second spectral feature is inadvertently or undesirably changed. Thus, the photolithography system **100** is designed to maintain a second spectral feature (such as the bandwidth) of the light beam **110** to within an acceptable range of values during scanning across the wafer **120** even while the first spectral feature (such as the wavelength) is being modified. In order to maintain the second spectral feature of the light beam **110** to within the acceptable range of values, the photolithography system **100** adjusts the second spectral feature of the light beam **110** so as to compensate for the undesirable change to the second spectral feature caused by the desired change to the first spectral feature. The modification to the second spectral feature (and other spectral features) is also implemented by and under control of the spectral feature selection apparatus **130**.

The modifications to the first spectral feature and the adjustments to the second spectral feature happen at each location or sub-area (for example, at each exposure field) of the wafer **120** upon instruction from the scanner **115**, and thus occur while the light beam **110** is being scanned across the wafer **120**. For example, the wavelength and the bandwidth of the light beam **110** can be adjusted for each sub-area (such as each exposure field) of the wafer **120**. These adjustments happen in a rapid manner in order to enable the adjustment to settle into a stable value within the time it takes to go from one sub-area of the wafer **120** to another sub-area of the wafer **120**.

In order to enable the rapid adjustment to the bandwidth for each sub-area of the wafer **120**, the spectral feature selection apparatus **130** has been redesigned to provide for more rapid adjustment of the bandwidth of the pulsed light beam **110** while the light beam **110** is being scanned across the wafer **120** to enable the adjustment of the bandwidth for each sub-area of the wafer **120**.

The spectral feature selection apparatus **130** can include a coarse spectral feature adjustment system **130**A and a fine spectral feature adjustment system **130**B. The coarse spectral feature adjustment system **130**A is used for coarse, large range, and slow control of the spectral feature (such as the bandwidth), and is collection of optical components that interact with the pulsed light beam **110**A produced by the optical source **104**. A coarse control means that the adjustment step to the spectral feature is relatively large when compared with the adjustment step used in fine control. The fine spectral feature adjustment system **130**B is used for fine, narrow range, and fast control of the spectral feature such as the bandwidth. A fine control means that the adjustment step to the spectral feature is relatively small when compared with the adjustment step used in coarse control. The fine spectral feature adjustment system **130**B can include an optical system that interacts optically with the pulsed light beam **110**A to control one or more spectral features. The fine bandwidth adjustment system **130**C can include a non-optical system that interacts with other aspects of the optical source **105** in a rapid manner to control one or more spectral features such as the bandwidth. For example, the fine spectral feature adjustment system **130**C can be configured to adjust aspects of the timing associated with the gas discharge chamber or chambers within the optical source **105** to thereby adjust the bandwidth of the pulsed light beam **110**.

Details about the photolithography system **100** are described next.

With reference again to FIG. **1**, the illumination system **150** includes an optical source **105** that produces the pulsed light beam **110** at a pulse repetition rate that is capable of being changed. The illumination system **150** includes a control system **185** that communicates with the optical source **105** and other features within the illumination system **150**. The illumination system **150** also communicates with the scanner **115** to control the operation of the illumination system **150** and aspects of the pulsed light beam **110**.

The control system **185** is operatively connected to the pulsed optical source **105** and to the spectral feature selection apparatus **130**. And, the scanner **115** includes a lithography controller **140** operatively connected to the control system **185** and components within the scanner **115**.

The pulse repetition rate of the pulsed light beam **110** is the rate at which pulses of the light beam **110** are produced by the optical source **105**. Thus, for example, the repetition rate of the pulsed light beam **110** is $1/\Delta t$, where Δt is the time between the pulses. The control system **185** is generally configured to control the repetition rate at which the pulsed light beam **110** is produced including modifying the repetition rate of the pulsed light beam as it is exposing the wafer **120** in the scanner **115**.

In some implementations, the scanner **115** triggers the optical source **105** (through the communication between the controller **140** and the control system **185**) to produce the pulsed light beam **110**, so the scanner **115** controls the repetition rate, spectral features such as the bandwidth or wavelength, and/or the dose by way of the controller **140** and the control system **185**. For example, the controller **140** sends a signal to the control system **185** to maintain the repetition rate of the light beam **110** within a particular range of acceptable rates. The scanner **115** generally maintains the repetition rate constant for each burst of pulses of the light beam **110**. A burst of pulses of the light beam **110** can correspond to an exposure field on the wafer **120**. A burst of pulses can include anywhere from 10 to 500 pulses, for example.

The critical dimension (CD) is the smallest feature size that can be printed on the wafer **120** by the system **100**. The CD depends on the wavelength of the light beam **110**. Thus, in order to maintain a uniform CD of the microelectronic features printed on the wafer **120**, and on other wafers exposed by the system **100**, the center wavelength of the light beam **110** should remain at an expected or target center wavelength or within a range of wavelengths around the target wavelength. Thus, in addition to maintaining the center wavelength at the target center wavelength or within a range of acceptable wavelengths about the target center wavelength, it is desirable to maintain the bandwidth of the light beam **110** (the range of wavelengths in the light beam **110**) to within an acceptable range of bandwidths.

In order to maintain the bandwidth of the light beam **110** to an acceptable range, or to adjust the bandwidth of the light beam **110**, the control system **185** is configured to determine an amount of adjustment to the bandwidth of the pulsed light beam **110**. Additionally, the control system **185** is configured to send a signal to the spectral feature selection apparatus **130** to move at least one optical component of the apparatus **130** (for example, a prism) to thereby change the bandwidth of the pulsed light beam **110** by the determined adjustment amount as the pulsed light beam **110** is exposing the wafer **120** to thereby compensate for the bandwidth variation caused by the modification of the pulse repetition rate of the pulsed light beam **110**.

The bandwidth of the pulsed light beam **110** can be changed in between any two bursts of pulses. Moreover, the time that it takes for the bandwidth to be changed from a first value to a second value and also to stabilize at the second value should be less than the time between the bursts of pulses. For example, if the period of time between bursts is 50 milliseconds (ms), then the total time to change the bandwidth from a first value to a second value and stabilize at the second value should be less than 50 ms. The control system **185** and the spectral feature selection apparatus **130** are designed to enable such a rapid change of the bandwidth, as discussed in detail below.

The controller **140** of the scanner **115** sends a signal to the control system **185** to adjust or modify an aspect (such as the bandwidth or the repetition rate) of the pulsed light beam **110** that is being scanned across the wafer **120**. The signal sent to the control system **185** can cause the control system **185** to modify an electrical signal sent to the pulsed optical source **105** or an electrical signal sent to the apparatus **130**. For example, if the pulsed optical source **105** includes a gas laser amplifier then the electrical signal provides a pulsed current to electrodes within one or more gas discharge chambers of the pulsed optical source **105**.

The wafer **120** is placed on the wafer stage **122** (also referred to as a table) and the stage **122** is connected to a positioner configured to accurately position the wafer **120** in accordance with certain parameters and under control of the controller **140**.

The photolithography system **100** can also include a measurement system **170**, which can include a sub-system that measures one or more spectral features (such as the bandwidth or wavelength) of the light beam **110**. Because of various disturbances applied to the photolithography system **100** during operation, the value of the spectral feature (such as the bandwidth or the wavelength) of the light beam **110** at the wafer **120** may not correspond to or match with the desired spectral feature (that is, the spectral feature that the scanner **115** expects). Thus, the spectral feature (such as a characteristic bandwidth) of light beam **110** is measured or estimated during operation by estimating a value of a metric from the optical spectrum so that an operator or an automated system (for example, a feedback controller) can use the measured or estimated bandwidth to adjust the properties of the optical source **105** and to adjust the optical spectrum of the light beam **110**. The sub-system of the measurement system **170** measures the spectral feature (such as the bandwidth and/or the wavelength) of the light beam **110** based on this optical spectrum.

The measurement system **170** receives a portion of the light beam **110** that is redirected from a beam separation device that is placed in a path between the optical source **105** and the scanner **115**. The beam separation device directs a first portion or percentage of the light beam **110** into the measurement system **170** and directs a second portion or percentage of the light beam **110** toward the scanner **115**. In some implementations, the majority of the light beam **110** is directed in the second portion toward the scanner **115**. For example, the beam separation device directs a fraction (for example, 1-2%) of the light beam **110** into the measurement system **170**. The beam separation device can be, for example, a beam splitter.

The pulses of the light beam **110** are centered around a wavelength that is in the deep ultraviolet (DUV) range, for example, with wavelengths of 248 nanometers (nm) or 193 nm. The size of the microelectronic features patterned on the wafer **120** depends on the wavelength of the pulsed light beam **110**, with a lower wavelength resulting in a small minimum feature size or critical dimension. When the wavelength of the pulsed light beam **110** is 248 nm or 193 nm, the minimum size of the microelectronic features can be, for example, 50 nm or less. The bandwidth that is used for analysis and control of the pulsed light beam **110** can be the actual, instantaneous bandwidth of its optical spectrum **300** (or emission spectrum), as shown in FIG. **3**. The optical spectrum **300** contains information about how the optical energy or power of the light beam **110** is distributed over different wavelengths (or frequencies). The optical spectrum **300** of the light beam **110** is depicted in the form of a diagram where the spectral intensity (not necessarily with an absolute calibration) is plotted as a function of the wavelength or optical frequency. The optical spectrum **300** can be referred to as the spectral shape or intensity spectrum of the light beam **110**. Spectral properties or features of the light beam **110** include any aspect or representation of the intensity spectrum. For example, bandwidth is a spectral feature. The bandwidth of the light beam is a measure of the width of this spectral shape, and this width can be given in terms of wavelength or frequency of the laser light. Any suitable mathematical construction (that is, metric) related to the details of the optical spectrum **300** can be used to estimate a value that characterizes the bandwidth of the light beam. For example, the full width of the spectrum at a fraction (X) of the maximum peak intensity of the spectral shape (referred to as FWXM) can be used to characterize the light beam bandwidth. As another example, the width of the spectrum that contains a fraction (Y) of the integrated spectral intensity (referred to as EY) can be used to characterize the light beam bandwidth.

The light beam **110** is directed through a beam preparation system **112**, which can include optical elements that modify aspects of the light beam **110**. For example, the beam preparation system **112** can include reflective and/or refractive optical elements, optical pulse stretchers, and optical apertures (including automated shutters).

The spectral feature selection apparatus **130** is placed at a first end of the optical source **105** to interact with a light beam **110**A produced by the optical source **105**. The light beam **110**A is a beam produced at one end of the resonators within the optical source **105** and can be a seed beam produced by a master oscillator, as discussed below. The spectral feature selection apparatus **130** is configured to finely tune the spectral properties of the pulsed light beam **110** by tuning or adjusting one or more spectral features (such as the bandwidth or wavelength) of the pulsed light beam **110**A.

Referring also to FIG. **4**, the wafer **120**, **220** is irradiated by the light beam **110**. The lithography exposure apparatus **115** includes an optical arrangement that includes an illuminator system **129** having, for example, one or more condenser lenses, a mask **134**, and an objective arrangement **132**. The mask **134** is movable along one or more directions, such as along a Z_L direction (which generally corresponds to the axial direction of the light beam **110**) or in an X_L-Y_L plane that is perpendicular to the Z_L direction. The objective arrangement **132** includes a projection lens and enables the image transfer to occur from the mask **134** to the photoresist on the wafer **120**. The illuminator system **129** adjusts the range of angles for the light beam **110** impinging on the mask **134**. The illuminator system **129** also homogenizes (makes uniform) the intensity distribution of the light beam **110** across the mask **134**.

The lithography apparatus **115** can include, among other features, a lithography controller **140**, air conditioning devices, and power supplies for the various electrical components. The lithography controller **140** controls how layers are printed on the wafer **120**.

In some implementations, an immersion medium can be supplied to cover the wafer **120**. The immersion medium can be a liquid (such as water) for liquid immersion lithography. In other implementations in which the lithography is a dry system, the immersion medium can be a gas such as dry nitrogen, dry air, or clean air. In other implementations, the wafer **120** can be exposed within a pressure-controlled environment (such as a vacuum or partial vacuum).

Referring again to FIG. **4**, a process program or recipe determines the length of the exposure on the wafer **120**, the mask **134** used, as well as other factors that affect the exposure. During lithography, a plurality of pulses of the light beam **110** illuminate the same area of the wafer **120** to form an illumination dose. The number of pulses N of the light beam **110** that illuminate the same area can be referred to as an exposure window **400** and the size of the window **400** can be controlled by an exposure slit **405** placed before the mask **134**. The slit **405** can be designed like a shutter and can include a plurality of blades that can be opened and closed. And, the size of the exposed area is determined by the distance between the blades in the non-scanning direction and also by the length (distance) of the scan in the scanning direction. In some implementations, the value of N is in the tens, for example, from 10-100 pulses. In other implementations, the value of N is greater than 100 pulses, for example, from 100-500 pulses.

One or more of the wafer stage **122**, the mask **134**, and the objective arrangement **132** are fixed to associated actuation systems to thereby form a scanning arrangement (or scanning optical system). In the scanning arrangement, one or more of the mask **134**, the objective arrangement **132**, and the wafer **120** (via the stage **122**) are moved relative to each other during the exposure to scan the exposure window **400** across an exposure field **223**.

Referring again to FIG. **1**, the photolithography system **100** also includes a wafer metrology apparatus **145** that is configured to determine a value of the lithography performance parameter PP for each sub-area (for example, for each exposure field **223**) of the wafer **120**, **220**. The metrology apparatus **145** is connected to the control system **185** so that the control system **185** receives the values of the lithography performance parameter PP for each wafer sub-area. The control system **185** can store the values of the lithography performance parameter PP for each wafer sub-area.

In some implementations, the metrology apparatus **145** is configured to be used in an offline mode in which the wafer **120**, **220** is analyzed after the wafer **120**, **220** has been patterned by the light beam **110**. The data obtained by such a scan can be used by the control system **185** for one or more wafers that will be scanned in the future.

In other implementations, the metrology apparatus **145** is used in an online mode in which the wafer **120**, **220** is analyzed while the wafer **120**, **220** is being patterned by the light beam **110**. For example, the exposure field of the wafer **120**, **220** could be probed in between bursts of the light beam **110**.

Referring again to FIG. **1**, the metrology apparatus **145** can be any apparatus that can probe the lithography performance parameter PP.

For example, if the performance parameter PP that is being monitored is the wafer topography, then the metrology apparatus **145** can be the scanner **115**, which can perform such monitoring during exposure or between scans of the wafer **120**. The topography of the wafer **120** can be controlled by adjusting the wavelength of the light beam **110**.

The metrology apparatus **145** can be a self-contained system such as a high resolution scanning electron microscope (SEM) that is designed for high resolution imaging, to be able to display feature sizes of less than, for example 1 nm. The SEM is a type of electron microscope that produces images of a sample (in this case, the wafer **120**) by scanning the wafer **120** with a focused beam of electrons. The SEM can achieve resolution better than 1 nanometer (nm).

The wafer **120** can be observed in any suitable environment such as in high vacuum, in low vacuum, (in environmental SEM) in wet conditions and at a wide range of cryogenic or elevated temperatures. The most common mode of detection is by secondary electrons emitted by atoms excited by the electron beam. The number of secondary electrons is a function of the angle between the surface of the wafer **120** and the electron beam. In other systems, back-scattered electrons or x-rays can be detected.

The metrology apparatus **145** can employ scanning white light interferometry, which provides quantitative noncontact, three dimensional measurements of the wafer **120**. In this technique, a white light beam passes through a filter and then a microscope objective lens to the surface of the wafer **120**. The light reflecting back from the surface of the wafer **120** is combined with a reference beam and captured for software analysis within the apparatus **145**. After obtaining data for each point, the apparatus **145** can generate a three dimensional image (topography) of the surface of the wafer **120**. Such a topographical map of the wafer **120** enables the measurement of these other lithography performance parameters as well: local step height, critical dimensions (CD), overlay, multilayer film thickness and optical properties, combined topography and film thickness, and wafer bow.

In other implementations, the metrology apparatus **145** is a scatterometer that transmits a pulse of energy toward the wafer **120** and measures the reflected or diffracted energy from the wafer **120**. The scatterometer can combine a measurement of overlay, focus, and CD in one sensor. In some implementations, the metrology apparatus **145** is the YieldStar S-250D (made by ASML Netherlands B. V. of Veldhoven, The Netherlands), which is a standalone metrology tool that allows measurement of on-product overlay and focus using diffraction based overlay and diffraction based focus techniques as well as the optional capability to measure CD.

In some implementations, the metrology apparatus **145** is an overlay metrology apparatus that determines whether the separate patterns of materials placed on each layer of the wafer **120** are aligned correctly. For example, the overlay metrology apparatus determines whether the contacts, lines, and transistors of each layer of the wafer line up with each other. Misalignment of any kind between the patterns can cause short circuits and connection failures, which in turn would impact yield and profit margins. Thus, in practice, the overlay metrology apparatus is used after each layer is formed on the wafer **120** but after the second layer is formed. The overlay metrology apparatus measures a relative position of the most recently formed (that is, the current) layer on the wafer to a previously formed layer on the wafer, where the most recently formed layer is formed on the previously formed layer. The relative position between the current wafer layer and the previously formed wafer layer is measured for each location at which the light beam exposes the wafer (if the characteristic of the light beam **110** measured at the wafer **120** corresponds to the location).

The metrology apparatus **145** can measure Critical Dimension (CD), which correlates to the printed feature size. SEMs and scatterometry tools can be used for measuring CD. The metrology apparatus **145** can measure overlay to check for image placement error relative to design intent and/or previously patterned layers. Optical and diffraction based tools can be used for measuring overlay.

Referring to FIG. **5**A, in some implementations, the spectral feature selection apparatus **130** includes a set of optical features or components **500**, **505**, **510**, **515**, **520** arranged to optically interact with the pulsed light beam **110**A and a control module **550** that includes electronics in the form of any combination of firmware and software. The optical components **500**, **505**, **510**, **515**, **520** can be configured to provide a coarse spectral feature adjustment system **130**A; and, if the adjustment of such components is rapid enough, it can be configured to provide a fine spectral feature adjustment system **130**B. Although not shown in FIG. **5**A, it is possible for the spectral feature selection apparatus **130** to include other optical features or other non-optical features for providing fine spectral feature control.

The control module **550** is connected to one or more actuation systems **500**A, **505**A, **510**A, **515**A, **520**A physically coupled to respective optical components **500**, **505**, **510**, **515**, **520**. The optical components of the apparatus **130** include a dispersive optical element **500**, which can be a grating, and a beam expander **501** made of a set of refractive optical elements **505**, **510**, **515**, **520**, which can be prisms. The grating **500** can be a reflective grating that is designed to disperse and reflect the light beam **110**A; accordingly, the grating **500** is made of a material that is suitable for interacting with a pulsed light beam **110**A having a wavelength in the DUV range. Each of the prisms **505**, **510**, **515**, **520** is a transmissive prism that acts to disperse and redirect the light beam **110**A as it passes through the body of the prism. Each of the prisms can be made of a material (such as, for example, calcium fluoride) that permits the transmission of the wavelength of the light beam **110**A. Although four refractive optical elements **505**, **510**, **515**, **520** are shown, it is possible for fewer than four or more than four to be used in the beam expander **501**.

The prism **520** is positioned farthest from the grating **500** while the prism **505** is positioned closest to the grating **500**. The pulsed light beam **110**A enters the apparatus **130** through an aperture **555**, and then travels through the prism **520**, the prism **510**, and the prism **505**, in that order, prior to impinging upon a diffractive surface **502** of the grating **500**. With each passing of the beam **110**A through a consecutive prism **520**, **515**, **510**, **505**, the light beam **110**A is optically magnified and redirected (refracted at an angle) toward the next optical component. The light beam **110**A is diffracted and reflected from the grating **500** back through the prism **505**, the prism **510**, the prism **515**, and the prism **520**, in that order, prior to passing through the aperture **555** as the light beam **110**A exits the apparatus **130**. With each passing through the consecutive prisms **505**, **510**, **515**, **520** from the grating **300**, the light beam **110**A is optically compressed as it travels toward the aperture **555**.

Referring to FIG. **5**B, the rotation of a prism P (which can be any one of prisms **505**, **510**, **515**, or **520**) of the beam expander **501** changes an angle of incidence at which the light beam **110**A impinges upon the entrance surface H(P) of that rotated prism P. Moreover, two local optical qualities, namely, an optical magnification OM(P) and a beam refraction angle δ (P), of the light beam **110**A through that rotated prism P are functions of the angle of incidence of the light beam **110**A impinging upon the entrance surface H(P) of that rotated prism P. The optical magnification OM(P) of the light beam **110**A through the prism P is the ratio of a transverse wide Wo(P) of the light beam **110**A exiting that prism P to a transverse width Wi(P) of the light beam **110**A entering that prism P.

A change in the local optical magnification OM(P) of the light beam **110**A at one or more of the prisms P within the beam expander **501** causes an overall change in the optical magnification OM **565** of the light beam **110**A through the beam expander **501**. The optical magnification OM **565** of the light beam **110**A through the beam expander **501** is the ratio of the transverse width Wo of the light beam **110**A exiting the beam expander **501** to a transverse width Wi of the light beam **110**A entering the beam expander **501**.

Additionally, a change in the local beam refraction angle δ (P) through one or more of the prisms P within the beam expander **501** causes an overall change in an angle of incidence of **562** of the light beam **110**A at the surface **502** of the grating **500**.

The wavelength of the light beam **110**A can be adjusted by changing the angle of incidence **562** at which the light beam **110**A impinges upon the diffractive surface **502** of the grating **500**. The bandwidth of the light beam **110**A can be adjusted by changing the optical magnification **565** of the light beam **110**.

The spectral feature selection apparatus **130** is redesigned to provide for more rapid adjustment of the bandwidth of the pulsed light beam **110** while the light beam **110** is being scanned across the wafer **120** by the scanner **115**. The spectral feature selection apparatus **130** can be redesigned with one or more new actuation systems for more effectively and more rapidly rotating one or more of the optical components **500**, **505**, **510**, **515**, **520**.

For example, the spectral feature selection apparatus **130** includes a new actuation system **520**A for more effectively and more rapidly rotating the prism **520**. The new actuation system **520**A can be designed in a manner that increases the speed with which the prism **520** is rotated. Specifically, the axis of rotation of the prism **520** mounted to the new actuation system **520**A is parallel with a rotatable motor shaft **522**A of the new actuation system **520**A. In other implementations, the new actuation system **520**A can be designed to include an arm that is physically linked to the motor shaft **522**A at one end and physically linked to the prism **520** at the other end to provide additional leverage for rotating the prism **520**. In this way, the optical magnification OM of the light beam **110**A is made to be more sensitive to rotation of the prism **520**.

In some implementations, the prism **505** is flipped relative to the prior design of the beam expander to provide for more rapid adjustment of the bandwidth. In these cases, the bandwidth change becomes relatively faster (when compared with prior designs of the apparatus **130**) with a relatively smaller rotation of the prism **520**. The change in optical magnification per unit rotation of the prism **520** is increased in the redesigned spectral feature selection apparatus **130** when compared with prior spectral feature selection apparatuses.

The apparatus **130** is designed to adjust the wavelength of the light beam **110**A that is produced within the resonator or resonators of the optical source **105** by adjusting an angle **562** of incidence of at which the light beam **110**A impinges upon the diffractive surface **502** of the grating **500**. Specifically, this can be done by rotating one or more of the prisms **505**, **510**, **515**, **520** and the grating **500** to thereby adjust the angle of incidence **562** of the light beam **110**A.

Moreover, the bandwidth of the light beam **110**A that is produced by the optical source **105** is adjusted by adjusting the optical magnification OM **565** of the light beam **110**A. Thus, the bandwidth of the light beam **110**A can be adjusted by rotating one or more of the prisms **505**, **510**, **515**, **520**, which causes the optical magnification **565** of the light beam **110**A to change.

Because the rotation of a particular prism P causes a change in both the local beam refraction angle δ (P) and the local optical magnification OM(P) at that prism P, the control of wavelength and bandwidth are coupled in this design.

Additionally, the bandwidth of the light beam **110**A is relatively sensitive to the rotation of the prism **520** and relatively insensitive to rotation of the prism **505**. This is because any change in the local optical magnification OM(**520**) of the light beam **110**A due to the rotation of the prism **520** is multiplied by the product of the change in the optical magnification OM(**515**), OM(**510**), OM(**505**), respectively, in the other prisms **515**, **510**, and **505** because those prisms are between the rotated prism **520** and the grating **500**, and the light beam **110**A must travel through these other prisms **515**, **510**, **505** after passing through the prism **520**. On the other hand, the wavelength of the light beam **110**A is relatively sensitive to the rotation of the prism **505** and relatively insensitive to the rotation of the prism **520**.

For example, in order to change the bandwidth without changing the wavelength, the optical magnification **565** should be changed without changing the angle of incidence **562**, and this can be achieved by rotating the prism **520** by a large amount and rotating the prism **505** by a small amount.

The control module **550** is connected to one or more actuation systems **500**A, **505**A, **510**A, **515**A, **520**A that are physically coupled to respective optical components **500**, **505**, **510**, **515**, **520**. Although an actuation system is shown for each of the optical components it is possible that some of the optical components in the apparatus **130** are either kept stationary or are not physically coupled to an actuation system. For example, in some implementations, the grating **500** can be kept stationary and the prism **515** can be kept stationary and not physically coupled to an actuation system.

Each of the actuation systems **500**A, **505**A, **510**A, **515**A, **520**A includes one or more actuators that are connected to its respective optical components. The adjustment of the optical components causes the adjustment in the particular spectral features (the wavelength and/or bandwidth) of the light beam **110**A. The control module **550** receives a control signal from the control system **185**, the control signal including specific commands to operate or control one or more of the actuation systems. The actuation systems can be selected and designed to work cooperatively.

Each of the actuators of the actuation systems **500**A, **505**A, **510**A, **515**A, **520**A is a mechanical device for moving or controlling the respective optical component. The actuators receive energy from the module **550**, and convert that energy into some kind of motion imparted to the respective optical component. For example, the actuation systems can be any one of force devices and rotation stages for rotating one or more of prisms of a beam expander. The actuation systems can include, for example, motors such as stepper motors, valves, pressure-controlled devices, piezoelectric devices, linear motors, hydraulic actuators, voice coils, etc.

The grating **500** can be a high blaze angle Echelle grating, and the light beam **110**A incident on the grating **500** at any angle of incidence **562** that satisfies a grating equation will be reflected (diffracted). The grating equation provides the relationship between the spectral order of the grating **500**, the diffracted wavelength (the wavelength of the diffracted beam), the angle of incidence **562** of the light beam **110**A onto the grating **500**, the angle of exit of the light beam **110**A diffracted off the grating **500**, the vertical divergence of the light beam **110**A incident onto the grating **500**, and the groove spacing of the diffractive surface of the grating **500**. Moreover, if the grating **500** is used such that the angle of incidence **562** of the light beam **110**A onto the grating **500** is equal to the angle of exit of the light beam **110**A from the grating **500**, then the grating **500** and the beam expander (the prisms **505**, **510**, **515**, **520**) are arranged in a Littrow configuration and the wavelength of the light beam **110**A reflected from the grating **500** is the Littrow wavelength. It can be assumed that the vertical divergence of the light beam **110**A incident onto the grating **500** is near zero. To reflect the nominal wavelength, the grating **500** is aligned, with respect to the light beam **110**A incident onto the grating **500**, so that the nominal wavelength is reflected back through the beam expander (the prisms **505**, **510**, **515**, **520**) to be amplified in the optical source **105**. The Littrow wavelength can then be tuned over the entire gain bandwidth of the resonators within optical source **105** by varying the angle of incidence **562** of the light beam **110**A onto the grating **500**.

Each of the prisms **505**, **510**, **515**, **520** is wide enough along the transverse direction of the light beam **110**A so that the light beam **110**A is contained within the surface at which it passes. Each prism optically magnifies the light beam **110**A on the path toward the grating **500** from the aperture **555**, and therefore each prism is successively larger in size from the prism **520** to the prism **505**. Thus, the prism **505** is larger than the prism **510**, which is larger than the prism **515**, and the prism **520** is the smallest prism.

The prism **520** that is the farthest from the grating **500**, and is also the smallest in size, is mounted on the actuation system **520**A, and specifically to the rotation shaft **522**A, which causes the prism **520** to rotate, and such rotation changes the optical magnification of the light beam **110**A impinging upon the grating **500** to thereby modify the bandwidth of the light beam **110**A output from the apparatus **130**. The actuation system **520**A is designed as a rapid actuation system **520**A because it includes a rotary stepper motor that includes the rotation shaft **522**A to which the prism **520** is fixed. The rotation shaft **522**A rotates about its shaft axis, which is parallel with the rotation axis of the prism **520**. Moreover, because the actuation system **520**A includes the rotary stepper motor, it lacks any mechanical memory and also lacks an energy ground state. Each location of the rotation shaft **522**A is at the same energy as each of the other locations of the rotation shaft **522**A and the rotation shaft **522**A lacks a preferred resting location with a low potential energy.

In some implementations, the actuation system **510**A (to which the prism **510** is mounted) can be a rapid actuation system similar to the rapid actuation system **520**A. In this way, the actuation system **510**A can include a rotation shaft **512**A, which causes the prism **510** to rotate, and such rotation changes the optical magnification of the light beam **110**A impinging upon the grating **500** to thereby modify the bandwidth of the light beam **110**A output from the apparatus **130**. The actuation system **510**A is therefore designed as a rapid actuation system (similarly to system **520**A) because it includes a rotary stepper motor that includes the rotation shaft **512**A to which the prism **510** is fixed. The rotation shaft **512**A rotates about its shaft axis, which is parallel with the rotation axis of the prism **510**. Moreover, because the actuation system **510**A includes the rotary stepper motor, it lacks any mechanical memory and also lacks an energy ground state. Each location of the rotation shaft **512**A is at the same energy as each of the other locations of the rotation shaft **512**A and the rotation shaft **512**A lacks a preferred resting location with a low potential energy.

As discussed above, the bandwidth of the light beam **110**A is relatively sensitive to the rotation of the prism **520** and relatively insensitive to rotation of the prism **505**. This is because any change in the local optical magnification OM(**520**) of the light beam **110**A due to the rotation of the prism **520** is multiplied by the product of the change in the optical magnification OM(**515**), OM(**510**), OM(**505**), respectively, in the other prisms **515**, **510**, and **505** because those prisms are between the rotated prism **520** and the grating **500**, and the light beam **110**A must travel through these other prisms **515**, **510**, **505** after passing through the prism **520**. On the other hand, the wavelength of the light beam **110**A is relatively sensitive to the rotation of the prism **505** and relatively insensitive to the rotation of the prism **520**. Thus, the wavelength can be coarsely changed by rotating the prism **505**, and the prism **520** can be rotated (in a coarse manner). The angle of incidence **562** of the light beam **110**A is changed due to the rotation of the prism **505** and the rotation of the prism **520** offsets the change in magnification caused by the rotation of the prism **505**. Moreover, the newly designed rapid actuation system **520**A enables the bandwidth to be rapidly changed to quickly offset the unwanted change in magnification. Additionally, if the bandwidth needs to be more finely controlled, then the prism **510** can be rapidly rotated using the newly designed rapid actuation system **510**A. It is also possible to more finely control the wavelength by rotating the prism **515** with the actuation system **515**A, which can include a piezo-electric stage.

The prism **520** can be used for coarse, large range, and slow bandwidth control. By contrast, the bandwidth can be controlled in a fine and narrow range and even more rapidly by controlling the prism **510**.

In some implementations, the spectral feature selection apparatus **130** can include a beam deflector such as a mirror that is placed at a location **503** between the beam expander **501** and the grating **500** and along the path of the light beam **110**A as it travels between the beam expander **501** and the grating **500**. The mirror is rotated under control of its own actuator system to change the angle of incidence **562** of the light beam **110**A impinging upon the diffractive surface **502** of the grating **500**. In this way, the mirror can be used to adjust the wavelength of the light beam **110**A without unwanted changes to the optical magnification **565** or the bandwidth of the light beam **110**A.

Referring to FIGS. **6**A and **6**B, in a first implementation, a spectral feature selection apparatus **630** is designed with a grating **600** and four prisms **605**, **610**, **615**, **620**. The grating **600** and the four prisms **605**, **610**, **615**, **620** are configured to interact with the light beam **110**A produced by the optical source **105** after the light beam **110**A passes through an aperture **655** of the apparatus **630**. The light beam **110**A travels along a path in an X_{SF}-Y_{SF} plane of the apparatus **630** from the aperture **655**, through the prism **620**, the prism **615**, the prism **610**, the prism **605**, and then is reflected from the grating **600**, and back through the prisms **605**, **610**, **615**, **620** before exiting the apparatus through the aperture **655**.

The prisms **605**, **610**, **615**, **620** are right-angled prisms through which the pulsed light beam **110**A is transmitted so that the pulsed light beam **110**A changes its optical magnification as it passes through each right-angled prism. The right-angled prism **620** that is farthest from the dispersive optical element **600** has the smallest hypotenuse of the plurality, and each consecutive right-angled prism closer to the dispersive optical element **600** has a larger or same size hypotenuse than the adjacent right-angled prism that is farther from the dispersive optical element.

For example, the prism **605** that is closest to the grating **600** is also the largest in size, for example, its hypotenuse has the largest extent of the four prisms **605**, **610**, **615**, **620**. The prism **620** that is farthest from the grating **600** is also the smallest in size, for example, its hypotenuse has the smallest extent of the four prisms **605**, **610**, **615**, **620**. It is possible for adjacent prisms to be the same size. But, each prism that is closer to the grating **600** should be at least as large or greater than in size its adjacent prism because the light beam **110**A is optically magnified as travels through the prism **620**, the prism **615**, the prism **610**, and the prism **605**, and thus the transverse extent of the light beam **110**A enlarges as the light beam **110**A gets closer to the grating **600**. The transverse extent of the light beam **110**A is the extent along the plane that is perpendicular to the propagation direction of the light beam **110**A. And, the propagation direction of the light beam **110**A is in the X_{SF}-Y_{SF} plane of the apparatus **630**.

The prism **605** is physically coupled to an actuation system **605**A that rotates the prism **605** about an axis that is parallel with the Z_{SF} axis of the apparatus **630**, the prism **610** is physically coupled to an actuation system **610**A that rotates the prism **610** about an axis that is parallel with the Z_{SF} axis, and the prism **620** is physically coupled to a rapid actuation system **620**A. The rapid actuation system **620**A is configured to rotate the prism **605** about an axis that is parallel with the Z_{SF} axis of the apparatus **630**.

The rapid actuation system **620**A includes a rotary stepper motor **621**A that has a rotation shaft **622**A and rotation plate **623**A fixed to the rotation shaft **622**A. The rotation shaft **622**A and therefore the rotation plate **623**A rotate about a shaft axis AR that is parallel with a center of mass (that corresponds to a rotation axis AP) of the prism **620** and is also parallel with the Z_{SF} axis of the apparatus **630**. Although not necessary, the shaft axis AR of the prism **620** can correspond with or align with the center of mass (the rotation axis AP) of the prism **620** along the X_{SF}-Y_{SF} plane. In some implementations, the center of mass (or rotation axis AP) of the prism **620** is offset from the shaft axis AR along the X_{SF}-Y_{SF} plane. By offsetting the shaft axis AR from the prism **620** center of mass, the position of the light beam **110**A can be adjusted to be at a particular position on the surface of the grating **600** whenever the prism **620** is rotated.

By mounting the prism **620** to the rotation plate **623**A, the prism **620** is directly rotated about its rotation axis AP as the shaft **622**A and rotation plate **623**A are rotated about their shaft axis AR. In this way, rapid rotation or control of the prism **620** is enabled when compared with a system that uses a linear stepper motor having a linearly translatable shaft (that is converted into a rotational motion using a flexure). Because a rotational step of the shaft **622**A (and plate **623**A) directly correlates to a rotational step of the prism **620** (without the imparting any a linear motion), the rotary stepper motor **621**A is able to rotate the prism **620** at a speed that enables more rapid adjustment of spectral features (such as the bandwidth) of the light beam **110**A and therefore the light beam **110**. The rotary design of the stepper motor **621**A imparts a purely rotational motion to the prism **620**, which is mounted without the use of any linear motion or flexure motion that are found on prior actuators for the prism **620**. Moreover, the use of a rotary shaft **622**A enables the prism **620** to be rotated about a full 360°, unlike the prior actuator that used a linear stepper motor plus a flexure design (in which the prism **620** could only be rotated about the angle determined from the flexure). In some implementations, in order to achieve a tuning of the bandwidth of the light beam **110**A in an acceptable range, the prism **620** is capable of being rotated by 15 degrees. The prism **620** can be rotated by larger than 15 degrees though it is not necessary with the current bandwidth range requirements.

In some implementations, the stepper motor **621**A can by a direct drive stepper motor. A direct drive stepper motor is a conventional electromagnetic motor that uses a built-in step motor functionality for position control. In other implementations in which a higher resolution in motion may be needed, the stepper motor **621**A can use a piezoelectric motor technology.

The stepper motor **621**A can be, for example, a rotary stage that is controlled with a motor controller using a variable-frequency drive control method to provide the rapid rotation of the prism **620**.

As discussed above, the advantage of using a rotary stepper motor **621**A is to obtain more rapid rotation of the prism **620** because the rotation axis AP of the prism **620** is parallel with the rotational shaft **622**A and also the shaft axis AR. Thus, for every unit rotation of the shaft **622**A, the prism **620** rotates by an incremental unit and the prism **620** rotates as fast as the rotational shaft **622**A can rotate. In some implementations, in order to increase the stability of this configuration, and increase the stability of the prism **620**, the rapid actuation system **620**A includes a position monitor **624**A that is configured to detect a position of the rotational shaft **622**A of the rotary stepper motor **621**A. The error between the measured position of the rotational shaft **622**A and the expected or target position of the rotational shaft **622**A correlates directly with the error in the position of the prism **620** and thus, this measurement can be used to determine the rotational error of the prism **620** (that is, the difference between actual rotation and commanded rotation) and to correct for this error during operation.

The control module **550** is connected to the position monitor **624**A to receive the value of the position of the rotational shaft **622**A and the control module **550** is also able to access a stored or current value of the commanded position of the rotational shaft **622**A so that the control module **550** can perform the calculation to determine the difference between the measured value of the position and the commanded position of the rotational shaft **622**A and also determine how to adjust the rotational shaft **622**A to reduce this error. For example, the control module **550** can determine a size of rotation as well as a direction of rotation of the rotational shaft **622**A to offset the error. Alternatively, it is possible for the control system **185** to perform this analysis.

The position monitor **624**A can be a very high resolution optical rotary encoder that is built integrally with the rotational plate **623**A. The optical rotary encoder uses optical sensing technology and on the rotation of an internal code disc that has opaque lines and patterns on it. For example, the plate **623**A is rotated (hence the name rotary encoder) in a beam of light such as a light emitting diode and the markings on the plate **623**A act as shutters blocking and unblocking the light. An internal photodiode detector senses the alternating light beam and the encoder's electronics convert the pattern into an electrical signal that is then passed on to the control module **550** through the output of the encoder **624**A.

In some implementations, the control module **550** can be designed with a rapid internal dedicated controller solely for operating the rotary stepper motor **621**A. For example, the rapid internal dedicated controller can receive the high resolution position data from the encoder **624**A and can send a signal directly to the rotary stepper motor **621**A to adjust the position of the shaft **622**A and thereby adjust the position of the prism **620**.

Referring also to FIG. **6**C, the illumination system **150** changes a spectral feature such as the bandwidth of the light beam **110**A under control of the control system **185**, which interfaces with the control module **550**. For example, in order to coarsely and broadly control the bandwidth of the light beam **110**A and the light beam **110**, the control module **550** sends a signal to the rotary stepper motor **621**A of the rapid actuation system **620**A to rotate the rotational shaft **622**A from a first angle θ**1** (on the left side of FIG. **6**C) to a second angle θ**2** (where Δθ=θ**2**−θ**1**) (on the right side of FIG. **6**C). And, this change of angle of the shaft **622**A is directly imparted to the plate **623**A, which is fixed to the shaft **622**A, and thereby also imparted to the prism **620**, which is fixed to the plate **623**A. The rotation of the prism **620** from θ**1** to θ**2** causes a corresponding change in the optical magnification OM **565** of the pulsed light beam **110**A that interacts with the grating **600** from OM**1** to OM**2**, and the change in the optical magnification **565** of the pulsed light beam **110**A causes a change in the bandwidth of the pulsed light beam **110**A (and the light beam **110** as well). The range of the bandwidth that can be achieved by rotating the prism **620** using this rapid actuation system **620**A can be a broad range and can be from about 100 femtometers (fm) to about 450 fm. The overall bandwidth range achievable can be at least 250 fm.

The rotation of the prism **620** associated with the rapid actuation system **620**A by one unit of rotation of the rotational shaft **622**A causes the bandwidth of the pulsed light beam **110**A to change by an amount that is less than a resolution of a bandwidth measurement device (for example, as a part of the measurement system **170**, which is discussed below) that measures the bandwidth of the pulsed light beam **110**. The prism **620** can be rotated by up to 15 degrees to achieve such a change in bandwidth. In practice, the amount of rotation of the prism **620** is constrained only by the optical layout of the other components of the apparatus **630**. For example, a rotation that is too large could cause the light beam **110**A to be displaced by an amount that is so large that the light beam **110**A does not impinge upon the next prism **615**. In some implementations, in order to achieve a tuning of the bandwidth of the light beam **110**A in an acceptable range, the prism **620** is capable of being rotated by 15 degrees, without risk of the light beam **110**A walking off any of the other prisms **605**, **610**, or **615**. The prism **620** can be rotated by larger than 15 degrees though it is not necessary with the current bandwidth range requirements.

Referring again to FIG. **6**A, the prism **610** can be mounted to an actuation system **610**A that causes the prism **410** to rotate, and such rotation of the prism **610** can provide for fine control of the wavelength of the light beam **110**A. The actuation system **610**A can include a rotary stepper motor that is controlled with a piezoelectric motor. The piezoelectric motor operates by making use of the converse piezoelectric effect in which a material produces acoustic or ultrasonic vibrations in order to produce a linear or rotary motion.

Alternatively, the prism **610** can be mounted to a rapid actuation system **610**A that includes a rotary stepper motor (like the rotary stepper motor **621**A that has a rotation shaft **622**A and rotation plate **623**A fixed to the rotation shaft **622**A). The rotation shaft and therefore the rotation plate rotate about a shaft axis that is parallel with a center of mass (that corresponds to a rotation axis AP) of the prism **610** and is also parallel with the Z_{SF} axis of the apparatus **630**. In this way, the rotation of the prism **610** can provide for more fine control of the bandwidth of the light beam **110**A.

The prism **615** that is closer to the grating **600**, and has a size that is either larger than or equal to the size of the prism **620**, can be fixed in space in some implementations. The next prism **610** that is closer to the grating **600** has a size that is either larger than or equal to the size of the prism **615**.

The prism **605** that is closest to the grating **610** has a size that is either larger than or equal to the size of the prism **610** (the prism **605** is the largest prism of the beam expander). The prism **605** can be mounted to an actuation system **605**A that causes the prism **605** to rotate and such rotation of the prism **605** can provide for coarse control of the wavelength of the light beam **110**A. For example, the prism **605** can be rotated by 1-2 degrees to tune the wavelength of the light beam **110**A (and thus the light beam **110**) from about 193.2 nanometers (nm) to about 193.5 nm. In some implementations, the actuation system **605**A includes a rotary stepper motor that includes a mounting surface (such as the plate **623**A) to which the prism **605** is fixed and a motor shaft that rotates the mounting surface. The motor of the actuation system **605**A can be a piezoelectric motor that is fifty times faster than a prior linear stepper motor and flexure combination design. Like the actuation system **620**A, the actuation system **605**A can include an optical rotary encoder that provides angular position feedback for the control system **185** or the control module **650**.

Referring to FIGS. **7**A and **7**B, in another implementation of the spectral feature selection apparatus **730**, a rapid actuation system **720**A is designed to rotate R the prism **720** of a beam expander that is farthest from the grating **700** about the shaft axis AR. Optionally or additionally, the actuation system **710**A associated with the prism **710** can also be a rapid actuation system that is designed like the rapid actuation system **720**A or **620**A.

The apparatus **730** includes an extending arm **725**A that has a first region **740**A that is mechanically linked to the rotational plate **723**A at the location of the shaft axis AR. The extending arm **725**A has a second region **745**A that is offset from the shaft axis AR along a direction in the X_{SF}-Y_{SF} plane (and thus along a direction that is perpendicular to the shaft axis AR) so that the second region **745**A is not intersected by the shaft axis AR. The prism **720** is mechanically linked to the second region **745**A.

Both the center of mass (the prism axis AP) of the prism **720** and the shaft axis AR remain parallel with the Z_{SF} axis of the apparatus **730**; however, the center of mass of the prism **720** is offset from the shaft axis AR. A rotation of the extending arm **725**A about the shaft axis AR by an angle Δθ imparts a combined movement to the prism **720**: a rotation R of the prism **720** about the shaft axis AR by an angle Δθ (see FIG. **5**C) within the X_{SF}-Y_{SF} plane, and a linear translation T to the prism **720** along a direction that lies within the X_{SF}-Y_{SF} plane of the apparatus **730**. In the example of FIG. **7**C, the prism **720** is rotated R from a first angle θ1 to a second angle θ2 and is translated T from a first position Pos**1** in the X_{SF}-Y_{SF} plane to a second position Pos**2** in the X_{SF}-Y_{SF} plane.

The linear translation T to the prism **720** thereby translates the light beam **110**A along a direction that is parallel with the longer axis **701** of the surface **702** of the grating **700**. The longer axis **701** also lies along the X_{SF}-Y_{SF} plane of the apparatus **730**. By performing this translation of the light beam **110**A, it is possible to control which area or region of the grating **700** is illuminated at the lower end of the range of possible optical magnifications OM. Moreover, the grating **700** and the surface **702** of the grating is non-uniform; namely, some regions of the surface **702** of the grating **700** impart a different change to the wavefront of the light beam **110**A than other regions of the surface **702** of the grating **700** and some regions of the surface **702** impart more distortion to the wavefront of the light beam **110**A than other regions of the surface **702**. The control system **185** (or control module **550**) can control the rapid actuation system **720**A to thereby adjust the linear translation T to the prism **720** and adjust the translation of the light beam **110**A along the longer axis **701** to take advantage of the non-uniformity of the grating **700** surface **702** and illuminate a higher distortion region of the grating surface **702** near one end of the grating surface **702** to raise the spectral bandwidth even more than the effect of simply lowering the optical magnification would achieve.

Additionally, the linear translation T to the prism **720** also translates the hypotenuse H (see FIG. **7**C) of the prism **720** during rotation of the prism **720** relative to the location of the light beam **110**A. The translation to the hypotenuse H therefore exposes new regions of the hypotenuse H to the light beam **110**A during operation of the apparatus **730**. Over the lifetime of the apparatus **730**, the prism **720** is rotated from one end of its rotation range to the other end and also more regions are exposed to the light beam **110**A, which reduces the amount of damage imparted to the prism **720** by the light beam **110**A.

Similar to the apparatus **630**, the spectral feature selection apparatus **730** also includes a grating **600**, and the beam expander includes the prisms **705**, **710**, **715**, which are positioned along the path of the light beam **110**A between the prism **720** and the grating **700**. The grating **700** and the four prisms **705**, **710**, **715**, **720** are configured to interact with the light beam **110**A produced by the optical source **105** after the light beam **110**A passes through an aperture **755** of the apparatus **730**. The light beam **110**A travels along a path in the X_{SF}-Y_{SF} plane of the apparatus **730** from the aperture **755**, through the prism **720**, the prism **715**, the prism **710**, the prism **705**, and then is reflected from the grating **700**, and back through the consecutive prisms **705**, **710**, **715**, **720** before exiting the apparatus **730** through the aperture **755**.

Referring to FIGS. **8**A-**8**D, in other implementations, a rapid actuation system **820**A is designed like the rapid actuation system **720**A but with an added secondary actuator **860**A. The secondary actuator **860**A is physically coupled to the prism **820** that is farthest from the grating **800**. The secondary actuator **860**A is configured to rotate the prism **820** about an axis AH that lies in the X_{SF}-Y_{SF} plane and also lies in the plane of a hypotenuse H of the prism **820**.

In some implementations, although not required the secondary actuator **860**A is controlled by the control module **650** (or the control system **185**). The secondary actuator **860**A can be a manual screw and flexure design that is not controlled by the control module **550** or the control system **185**. For example, the actuator **860**A could be set before the system **820**A is used or periodically can be changed manually in between uses of the system **820**A.

The prism **820** can therefore be rotated about the axis AH that lies in the X_{SF}-Y_{SF} plane to enable greater control over where the light beam **110**A enters the prism **820** and the hypotenuse H of the prism **820** in order to better maintain the path of the light beam **110**A through each of the prisms **815**, **810**, **805**, and the grating **800**. Specifically, rotation of the prism **820** about the axis AH enables the light beam **110**A to be more finely adjusted. For example, the prism **820** can be rotated about the axis AH to ensure that the retro-reflected (that is, diffracted) light beam **110**A from the grating **800** remains in the X_{SF}-Y_{SF} plane and is not displaced along the Z_{SF} axis of the apparatus **830** even if the prism **820** is rotated about the AP or AR axis. It is beneficial to have this Z_{SF} axis adjustment if the AP or AR axis is not perfectly aligned with the Z_{SF} axis. Additionally, it can be beneficial to rotate the prism **820** about the AH axis because the extending arm **825**A is a cantilever and it can sag or move in a manner along the Z_{SF} axis such that it deflects about the axis AH and the secondary actuator **860**A can be used to offset this deflection.

Referring to FIG. **9**, an exemplary optical source **905** is a pulsed laser source that produces a pulsed laser beam as the light beam **110**. The optical source **905** is a two-stage laser system that includes a master oscillator (MO) **900** that provides the seed light beam **110**A to a power amplifier (PA) **910**. The master oscillator **900** typically includes a gain medium in which amplification occurs and an optical feedback mechanism such as an optical resonator. The power amplifier **910** typically includes a gain medium in which amplification occurs when seeded with the seed laser beam from the master oscillator **900**. If the power amplifier **910** is designed as a regenerative ring resonator then it is described as a power ring amplifier (PRA) and in this case, enough optical feedback can be provided from the ring design. The spectral feature selection apparatus **130** receives the light beam **110**A from the master oscillator **900** to enable fine tuning of spectral parameters such as the center wavelength and the bandwidth of the light beam **110**A at relatively low output pulse energies. The power amplifier **910** receives the light beam **110**A from the master oscillator **900** and amplifies this output to attain the necessary power for output to use in photolithography.

The master oscillator **900** includes a discharge chamber having two elongated electrodes, a laser gas that serves as the gain medium, and a fan circulating the gas between the electrodes. A laser resonator is formed between the spectral feature selection apparatus **130** on one side of the discharge chamber, and an output coupler **915** on a second side of the discharge chamber to output the seed light beam **110**A to the power amplifier **910**.

The optical source **905** can also include a line center analysis module (LAM) **920** that receives an output from the output coupler **915**, and one or more beam modification optical systems **925** that modify the size and/or shape of the beam as needed. The line center analysis module **920** is an example of one type of measurement system within the measurement system **170** that can be used to measure the wavelength (for example, the center wavelength) of the seed light beam.

The power amplifier **910** includes a power amplifier discharge chamber, and if it is a regenerative ring amplifier, the power amplifier also includes a beam reflector or beam turning device **930** that reflects the light beam back into the discharge chamber to form a circulating path. The power amplifier discharge chamber includes a pair of elongated electrodes, a laser gas that serves as the gain medium, and a fan for circulating the gas between the electrodes. The seed light beam **110**A is amplified by repeatedly passing through the power amplifier **910**. The beam modification optical system **925** provides a way (for example, a partially-reflecting mirror) to in-couple the seed light beam **110**A and to out-couple a portion of the amplified radiation from the power amplifier to form the output light beam **110**.

The laser gas used in the discharge chambers of the master oscillator **900** and the power amplifier **910** can be any suitable gas for producing a laser beam around the required wavelengths and bandwidth. For example, the laser gas can be argon fluoride (ArF), which emits light at a wavelength of about 193 nm, or krypton fluoride (KrF), which emits light at a wavelength of about 248 nm.

The line center analysis module **920** monitors the wavelength of the output (the light beam **110**A) of the master oscillator **900**. The line center analysis module **920** can be placed at other locations within the optical source **905**, or it can be placed at the output of the optical source **905**.

The repetition rate of the pulses produced by the power amplifier **910** is determined by the repetition rate at which the master oscillator **900** is controlled by the control system **185**, under the instructions from the controller **140** in the scanner **115**. The repetition rate of the pulses output from the power amplifier **910** is the repetition rate seen by the scanner **115**.

As discussed above, it is possible to control the bandwidth both coarsely and finely using only optical elements such as those in FIG. **5**A. On the other hand, it is possible to control the bandwidth in a fine and narrow range, and rapidly, by controlling a differential timing between the activation of the electrodes within the MO **900** and the PRA **910** while controlling the bandwidth in a coarse and wide range by adjusting the angle of the prism **520** using the rapid actuation system **520**A.

Referring to FIG. **10**, details about the control system **185** are provided that relate to the aspects of the system and method described herein. The control system **185** can include other features not shown in FIG. **10**. In general, the control system **185** includes one or more of digital electronic circuitry, computer hardware, firmware, and software.

The control system **185** includes memory **1000**, which can be read-only memory and/or random access memory. Storage devices suitable for tangibly embodying computer program instructions and data include all forms of non-volatile memory, including, by way of example, semiconductor memory devices, such as EPROM, EEPROM, and flash memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM disks. The control system **185** can also include one or more input devices **1005** (such as a keyboard, touch screen, microphone, mouse, hand-held input device, etc.) and one or more output devices **1010** (such as a speaker or a monitor).

The control system **185** includes one or more programmable processors **1015**, and one or more computer program products **1020** tangibly embodied in a machine-readable storage device for execution by a programmable processor (such as the processors **1015**). The one or more programmable processors **1015** can each execute a program of instructions to perform desired functions by operating on input data and generating appropriate output. Generally, the processor **1015** receives instructions and data from memory **1000**. Any of the foregoing may be supplemented by, or incorporated in, specially designed ASICs (application-specific integrated circuits).

The control system **185** includes, among other components, a spectral feature analysis module **1025**, a metrology module **1027**, a lithography analysis module **1030**, a decision module **1035**, a light source actuation module **1050**, a lithography actuation module **1055**, and a beam preparation actuation module **1060**. Each of these modules can be a set of computer program products executed by one or more processors such as the processors **1015**. Moreover, any of the modules **1025**, **1030**, **1035**, **1050**, **1055**, **1060** can access data stored within the memory **1000**.

The spectral feature analysis module **1025** receives the output from the measurement system **170**. The metrology module **1027** receives the data from the metrology apparatus **145**. The lithography analysis module **1030** receives information from the lithography controller **140** of the scanner **115**. The decision module **1035** receives the outputs from the analyses modules (such as the modules **1025**, **1027**, and **1030**) and determines which actuation module or modules need to be activated based on the outputs from the analyses modules. The light source actuation module **1050** is connected to one or more of the optical source **105** and the spectral feature selection apparatus **130**. The lithography actuation module **1055** is connected to the scanner **115**, and specifically to the lithography controller **140**. The beam preparation actuation module **1060** is connected to one or more components of the beam preparation system **112**.

While only a few modules are shown in FIG. **10**, it is possible for the control system **185** to include other modules. Additionally, although the control system **185** is represented as a box in which all of the components appear to be co-located, it is possible for the control system **185** to be made up of components that are physically remote from each other. For example, the light source actuation module **1050** can be physically co-located with the optical source **105** or the spectral feature selection apparatus **130**.

In general, the control system **185** receives at least some information about the light beam **110** from the measurement system **170**, and the spectral feature analysis module **1025** performs an analysis on the information to determine how to adjust one or more spectral features (for example, the bandwidth) of the light beam **110** supplied to the scanner **115**. Based on this determination, the control system **185** sends signals to the spectral feature selection apparatus **130** and/or the optical source **105** to control operation of the optical source **105** via the control module **550**. In general, the spectral feature analysis module **1025** performs the analysis needed to estimate one or more spectral features (for example, the wavelength and/or the bandwidth) of the light beam **110**. The output of the spectral feature analysis module **1025** is an estimated value of the spectral feature that is sent to the decision module **1035**.

The spectral feature analysis module **1025** includes a comparison block connected to receive the estimated spectral feature and also connected to receive a spectral feature target value. In general, the comparison block outputs a spectral feature error value that represents a difference between the spectral feature target value and the estimated value. The decision module **1035** receives the spectral feature error value and determines how best to effect a correction to the system **100** in order to adjust the spectral feature. Thus, the decision module **1035** sends a signal to the light source actuation module **1050**, which determines how to adjust the spectral feature selection apparatus **130** (or the optical source **105**) based on the spectral feature error value. The output of the light source actuation module **1050** includes a set of actuator commands that are sent to the spectral feature selection apparatus **130**. For example, light source actuation module **1050** sends the commands to the control module **550**, which is connected to the actuation systems within the apparatus **530**.

Additionally, the lithography analysis module **1030** can receive instructions from the lithography controller **140** of the scanner **115** for example, to change one or more spectral features of the pulsed light beam **110** or to change a pulse repetition rate of the light beam **110**. The lithography analysis module **1030** performs an analysis on these instructions to determine how to adjust the spectral features and sends the results of the analysis to the decision module **1035**. The control system **185** causes the optical source **105** to operate at a given repetition rate. More specifically, the scanner **115** sends a trigger signal to the optical source **105** (by way of the control system (through the lithography analysis module **1030**) for every pulse (that is, on a pulse-to-pulse basis) and the time interval between those trigger signals can be arbitrary, but when the scanner **115** sends trigger signals at regular intervals then the rate of those signals is a repetition rate. The repetition rate can be a rate requested by the scanner **115**.

Referring to FIG. **11**, a procedure **1100** is performed by the photolithography system **100** to rapidly and independently control at least two spectral features of the pulsed light beam **110** to compensate for a variation in one or more lithography performance parameters at each sub-area of the wafer **120**. The independent control of the at least two spectral features means that if a first spectral feature should be adjusted for a particular sub-area of the wafer **120**, and the second spectral feature should be maintained for that particular sub-area of the wafer **120**, then the procedure **1100** takes the steps needed to maintain the second spectral feature within an acceptable range and it does this for each sub-area of the wafer **120**. Thus, the first spectral feature and the second spectral feature reach a stable value after any adjustments are needed in a particular sub-area of the wafer **120** and before the next sub-area of the wafer **120** is analyzed. This rapid analysis and adjustment takes place for each sub-area of the wafer **120** because the spectral feature selection system **130** has been redesigned to provide for more rapid adjustments to the spectral features of the pulsed light beam **110**. The procedure **1100** can be performed by the control system **185**.

The pulsed light beam **110** is produced (**1105**) for example, by the optical source **105**. The pulsed light beam **110** can be produced (**1105**) by directing seed light beam **110**A through the spectral feature selection system **130**.

For example, the pulsed light beam **110** can be produced from the optical source **905** by generating a first pulsed light beam **910**A from a first gas discharge stage (such as the master oscillator **900**) including selecting the first spectral feature of the pulsed light beam **910**A; directing the first pulsed light beam **910**A to a second gas discharge stage (such as the power amplifier **910**); and amplifying the first pulsed light beam in the second gas discharge stage to thereby produce the pulsed light beam **910** from the optical source **905**.

The pulsed light beam **110** is directed toward the wafer **120**, which is mounted to the stage **122** of the scanner **115**. For example, the pulsed light beam **110** produced by the optical source **105** is modified, as needed, and redirected by the beam preparation system **112** toward the scanner **115**.

The pulsed light beam **110** is scanned across the wafer **120** (**1110**), for example, by moving the pulsed light beam **110** and the wafer **120** relative to each other along the lateral plane (the X_L-Y_L plane). Specifically, the lithography controller **140** can send one or more signals to the actuation systems associated with the wafer stage **122**, the mask **134**, and the objective arrangement **132** to thereby move one or more of the mask **134**, the objective arrangement **132**, and the wafer **120** (via the stage **122**) relative to each other during the exposure to scan the exposure window **400** across each sub-area (for each exposure field **223**) of the wafer **220**.

A first sub-area of the wafer **120** is selected for exposure (**1115**) by the light beam **110** for lithographic processing. The sub-area of the wafer **120** that is selected can be an exposure field (such as the exposure field **223** of the wafer **220**). Or, the sub-area of the wafer **120** can correspond to that portion of the wafer **120** that interacts with a single pulse of the light beam **110**.

The lithography performance parameter at the wafer **120** for that selected sub-area of a wafer **120** is received (**1120**). For example, the control system **185** receives the performance parameter for the sub-area of the wafer **120** from the lithography controller **140**, which receives the data from the metrology apparatus **145**. The performance parameter at the wafer **120** can be received (**1120**) at each sub-area of the wafer **120** while scanning the pulsed light beam **110** across the wafer **120** or it can be received prior to scanning the pulsed light beam **110** across the wafer **120**.

The performance parameter that is received (**1120**) can be one or more of an error in a physical property of the wafer, a contrast of a feature formed on the wafer, a critical dimension at sub-area exposed to the pulsed light beam **110**, a placement (X, Y location relative to desired/target location) of a feature formed on the wafer **120** relative to a target or relative to an underlying feature (for example, an overlay), a photoresist profile, a side-wall angle, and a change in position of the wafer **120**.

The control system **185** analyzes the received lithography performance parameter (**1125**), for example, to determine whether it is outside an acceptable range of values. If the lithography performance parameter is outside an acceptable range of values (**1125**), then the control system **185** determines how to modify a first spectral feature of the light beam **110** in order to compensate for the unacceptable variation in the lithography performance parameter in that sub-area of the wafer **120**. The control system **185** sends a signal to the spectral feature selection apparatus **130** to change the first spectral feature of the light beam **110** (**1130**) by an amount that would compensate for the unacceptable variation in the lithography performance parameter.

Moreover, the control system **185** also analyzes whether the modification to the first spectral feature of the light beam **110** impacts the value of the second spectral feature of the light beam **110** and acts in a manner that would maintain the second spectral feature of the light beam **110** within an acceptable range. For example, the control system **185** may determine that the second spectral feature of the light beam **110** needs to be changed to offset an unwanted modification to the second spectral feature of the light beam **110** caused by the modification to the first spectral feature of the light beam **110**. The control system **185** therefore sends a signal to the spectral feature selection apparatus **130** to change the second spectral feature of the light beam (**1130**) by an amount that would compensate for this unwanted modification.

The control system **185** determines whether additional sub-areas of the wafer **120** need to be exposed (**1135**) by the light beam **110** for lithographic processing, and if additional sub-areas of the wafer **120** need to be exposed (**1135**), then the control system **185** selects a next sub-area of the wafer **120** (**1140**) as the sub-area to be exposed by the light beam

110 for lithographic processing. Thus, the procedure 1100 continues until the entire wafer 120 has been processed.

Moreover, the procedure 1100 can modify the first spectral feature of the pulsed light beam 110 (1130) by selectively reflecting the pulsed light beam 110A from a diffractive surface (such as the surface 502) of the spectral feature selection system 130.

The first spectral feature of the pulsed light beam can be modified (1130) and the second spectral feature of the pulsed light beam can be maintained (113) by directing the pulsed light beam through a plurality of prisms (such as the prisms 505, 510, 515, 520) toward a diffractive optical element (such as the grating 500) so that the pulsed light beam retro reflects off the diffractive optical element and back through the plurality of prisms. Additionally, at least two prisms in the beam expander can be rotated so that an angle of incidence 562 of the pulsed light beam 110 on the diffractive optical element is changed but the total magnification 565 of the pulsed light beam on the diffractive optical element is unchanged.

The first spectral feature of the light beam 110 can be modified (1130) by modifying the wavelength of the pulsed light beam. Moreover, the second spectral feature can be maintained (1130) by maintaining the bandwidth of the pulsed light beam 110 to within a range of bandwidths. For example, the bandwidth of the pulsed light beam 110 can be maintained to within ±10 femtometers (fm) or within ±1 fm.

The first spectral feature of the pulsed light beam 110 can be modified (1130) by rotating a first prism system of the spectral feature selection apparatus 130 through which the pulsed light beam 110A passes. For example, the control system 185 can send a signal to the control module 550 of the spectral feature selection apparatus 130 of FIG. 5A to rotate one or more prisms of the beam expander 501. For example, the prism 505 can be rotated for relatively coarse wavelength modification and the prism 510 can be rotated for relatively fine wavelength modification. As another example, the prism 505 can be rotated for relatively coarse wavelength modification and the prism 515 can be rotated for relatively fine wavelength modification.

Moreover, the second spectral feature of the pulsed light beam 110 can be maintained (1130) by rotating a second prism system of the spectral feature selection apparatus 130 through which the pulsed light beam 110A passes. For example, the control system 185 can send a signal to the control module 550 of the spectral feature selection apparatus 130 of FIG. 5A to rotate one or more prisms of the beam expander 501. For example, the prism 520 can be rotated for relatively coarse bandwidth adjustment and the prism 510 can be rotated for relatively fine bandwidth adjustment using the rapid actuators discussed above.

A relatively coarse wavelength modification can be effected by an actuation step associated with that prism that is relatively larger than an actuation step used to provide a relatively fine wavelength modification. Similarly, a relatively coarse bandwidth adjustment can be effected by an actuation step associated with that prism that is relatively larger than an actuation step used to provide a relatively fine bandwidth modification.

The first spectral feature of the pulsed light beam 110 can be modified (1130) by rotating a mirror placed between the prism 505 and the grating 500 of the spectral feature selection apparatus 130 through which the pulsed light beam 110A passes. For example, the control system 185 can send a signal to the control module 550 of the spectral feature selection apparatus 130 of FIG. 5A to rotate the mirror.

The control system 185 can maintain the second spectral feature of the pulsed light beam 110 (1130) by adjusting the second spectral feature to compensate for changes of the second spectral feature due to the modification of the first spectral feature of the pulsed light beam 110 (1130). Moreover, the second spectral feature of the pulsed light beam 110 can be adjusted (1130) simultaneously with modifying the first spectral feature of the pulsed light beam 110 (1130).

The modification of the first spectral feature of the pulsed light beam 110 (1130) can cause a modification to a first condition of the pulsed light beam 110 at the wafer 120. For example, if the first spectral feature is the wavelength of the light beam 110, then modification of the wavelength causes a modification to a focal plane of the light beam 110 at the wafer 120. The maintaining of the second spectral feature of the pulsed light beam 110 (1130) can cause a second condition of the pulsed light beam 110 at the wafer 120 to be maintained at a particular level. For example, if the second spectral feature is the bandwidth of the light beam 110, then by maintaining the bandwidth of the light beam 110, a contrast attribute or depth of focus of the light beam 110 at the wafer 120 can thereby be maintained.

While the examples given above referred to the spectral feature selection apparatus of FIG. 5A, any of the designs for the spectral feature selection apparatuses of FIGS. 6A, 7A, and 8A could instead be used to perform one or more steps in the procedure 1100.

Additionally, during the procedure 1100, the control system 185 also performs a parallel procedure 1150, as shown in FIG. 12, for controlling one or more spectral features of the pulsed light beam 110 while the light beam 110 is being scanned across the wafer 120. This procedure 1150 performs independently of whether a lithography performance parameter is outside an acceptable range and thus does not take into account the lithography performance parameter. Nevertheless, the analysis performed by the control system 185 during the procedure 1150 can be used by the control system 185 to also determine how to analyze the received lithography performance parameter (1125) and modify the first spectral feature and maintain the second spectral feature (1130).

The procedure 1150 includes measuring one or more spectral features of the pulsed light beam 110 (1155) and determining whether any of the measured spectral features are outside of an acceptable range of values (1160). For example, the spectral feature analysis module 1025 of the control system 185 can receive the spectral feature measurement from the measurement system 170 (1155). The spectral feature analysis module 1025 can determine whether any of the spectral features are outside an acceptable range of values (1160). If any of the spectral features are outside an acceptable range of values, then those spectral features are adjusted (1165). For example, the decision module 1035 can send a signal to the light source actuation module 1050, which sends a signal to the spectral feature selection apparatus 130 to adjust one or more spectral features of the light beam 110 (1165). This adjustment can be coordinated with any adjustments that need to be made to account for the changes in the wafer characteristics (1130).

The procedure 1150 can be performed during the scanning and at regular intervals, for example, for each exposure field 223 or for each sub-area in which the steps 1120, 1125, 1130 are performed. Moreover, it is possible for the control system 185 to coordinate the adjustment to the first spectral feature needed to compensate for the lithography performance parameter variations (1130) with any required adjustment to the first spectral feature to ensure that the first spectral feature is within an acceptable range of values.

Other implementations are within the scope of the following claims.

What is claimed is:

1. An apparatus comprising:
- a spectral feature selection system that optically interacts with a pulsed light beam;
- a measurement system configured to measure one or more spectral features of the pulsed light beam;
- a metrology apparatus configured to determine at least one lithography performance parameter for each sub-area of a substrate, in which a sub-area is a portion of a total area of the substrate and in which a lithography performance parameter is a characteristic associated with the substrate or with the pulsed light beam as it interacts with the substrate; and
- a control system connected to the spectral feature selection system, the measurement system, and the metrology apparatus, and configured to, for each substrate sub-area:
  - receive the determined lithography performance parameter from the metrology apparatus and receive the one or more measured spectral features of the pulsed light beam from the measurement system;
  - analyze the determined lithography performance parameter for each sub-area of the substrate and analyze the one or more measured spectral features of the pulsed light beam; and
  - based on these analyses:
    - send a first signal to the spectral feature selection system to modify a first spectral feature of the pulsed light beam, wherein the modification of the first spectral feature takes into account the analysis of the one or more measured spectral features and wherein the first signal is sent based on a determination that the lithography performance parameter is outside an acceptable range; and
    - maintain a second spectral feature of the pulsed light beam to within a range of values of the second spectral feature by sending a second signal to the spectral feature selection system while the first spectral feature of the pulsed light beam is being modified.

2. The apparatus of claim 1, the control system is configured to send the first signal to the spectral feature selection system to modify the first spectral feature, where the first signal takes into account the analysis of the one or more measured spectral features, by determining whether any of the one or more measured spectral features are outside an acceptable range of values.

3. The apparatus of claim 1, wherein the first spectral feature of the pulsed light beam is the wavelength of the pulsed light beam and the second spectral feature of the pulsed light beam is the bandwidth of the pulsed light beam.

4. The apparatus of claim 1, wherein the measurement system is configured to receive a portion of the pulsed light beam that is directed toward the substrate.

5. The apparatus of claim 1, wherein the lithography performance parameter includes one or more of: a mean offset of a position of the substrate from a desired position, a stage vibration of the substrate, a position of the substrate that varies from central sub-areas of the substrate to sub-areas at an edge of the substrate, an error in a physical property of the substrate, a contrast of a feature formed on the substrate, a critical dimension at a substrate area exposed to the pulsed light beam, the placement of the feature formed on the substrate relative to a target or relative to an underlying feature, a photoresist profile, a side-wall angle, and a change in position of the substrate.

6. A method comprising:
- measuring one or more spectral features of a pulsed light beam that is directed toward a substrate of a lithography exposure apparatus;
- receiving at least one lithography performance parameter associated with each sub-area of the substrate as the pulsed light beam interacts with that sub-area, in which a sub-area is a portion of a total area of the substrate and in which a lithography performance parameter is a characteristic associated with the substrate or with the pulsed light beam as it interacts with the substrate;
- receiving the one or more measured spectral features of the pulsed light beam;
- analyzing the determined lithography performance parameter at each sub-area of the substrate;
- analyzing the one or more measured spectral features of the pulsed light beam; and
- based on these analyses:
  - modifying a first spectral feature of the pulsed light beam, wherein modification of the first spectral feature takes into account the analysis of the one or more measured spectral features and wherein modification of the first spectral feature is based on a determination that the lithography performance parameter is outside an acceptable range; and
  - maintaining a second spectral feature of the pulsed light beam to within a range of values of the second spectral feature while the first spectral feature of the pulsed light beam is being modified.

7. The method of claim 6, wherein modification of the first spectral feature takes into account the analysis of the one or more measured spectral features includes determining whether any of the one or more measured spectral features are outside an acceptable range of values.

8. The method of claim 6, wherein modifying the first spectral feature of the pulsed light beam comprises modifying the wavelength of the pulsed light beam and maintaining the second spectral feature of the pulsed light beam comprises maintaining the bandwidth of the pulsed light beam to within a range of bandwidth values.

9. The method of claim 6, wherein measuring the one or more spectral features of the pulsed light beam comprises measuring the wavelength of the pulsed light beam.

10. The method of claim 6, wherein measuring the one or more spectral features of the pulsed light beam comprises measuring the bandwidth of the pulsed light beam.

11. The method of claim 6, wherein modifying the first spectral feature of the pulsed light beam comprises ensuring that the first spectral feature is within an acceptable range of values.

12. The method of claim 6, wherein measuring the one or more spectral features of the pulsed light beam comprises estimating a value of a metric of an optical spectral of the pulsed light beam.

13. A photolithography apparatus comprising:
- a spectral feature selection system that optically interacts with a pulsed light beam;
- a metrology apparatus configured to determine at least one lithography performance parameter at each sub-area of a substrate, in which a sub-area is a portion of a total area of the substrate and in which a lithography performance parameter is a characteristic associated with the substrate or with the pulsed light beam as it interacts with the substrate; and

a control system connected to the spectral feature selection system and the metrology apparatus, and configured to, at each substrate sub-area:

receive the determined lithography performance parameter;

analyze the determined lithography performance parameter; and

based on the analysis of the determined lithography performance parameter:

modify a wavelength of the pulsed light beam by sending a first signal to the spectral feature selection system, wherein the modification of the wavelength causes a change in a bandwidth of the pulsed light beam; and

maintain the bandwidth of the pulsed light beam to within an acceptable range of values while the wavelength is being modified.

14. The apparatus of claim **13**, wherein maintaining the bandwidth of the pulsed light beam to within an acceptable range of values comprises adjusting the bandwidth of the pulsed light beam to compensate for the change to the bandwidth that is caused by the modification of the wavelength, wherein adjusting the bandwidth comprises sending a second signal to the spectral feature selection system while the wavelength of the pulsed light beam is being modified.

15. The apparatus of claim **14**, wherein:

modifying the wavelength of the pulsed light beam comprises rotating a wavelength prism through which the pulsed light beam passes to change an angle of incidence between the pulse light beam and a grating; and

adjusting the bandwidth of the pulsed light beam comprises rotating a bandwidth prism through which the pulsed light beam passes by an amount that offsets a change in magnification caused by the rotation of the wavelength prism.

16. The apparatus of claim **13**, wherein the lithography performance parameter includes one or more of: a mean offset of a position of the substrate from a desired position, a stage vibration of the substrate, a position of the substrate that varies from central sub-areas of the substrate to sub-areas at an edge of the substrate, an error in a physical property of the substrate, a contrast of a feature formed on the substrate, a critical dimension at a substrate area exposed to the pulsed light beam, the placement of the feature formed on the substrate relative to a target or relative to an underlying feature, a photoresist profile, a side-wall angle, and a change in position of the substrate.

17. The apparatus of claim **13**, wherein spectral feature selection system includes:

a grating and a beam expander including a plurality of prisms configured so that the pulsed light beam interacts with each of the grating and the prisms of the beam expander; and

an actuation system in communication with the control system, the actuation system including a plurality of actuators, each actuator coupled to one of the prisms to cause the prism to rotate relative to the pulsed light beam under control of the control system.

18. A method comprising:

receiving at least one lithography performance parameter associated with each sub-area of the substrate as the pulsed light beam interacts with that sub-area, in which a sub-area is a portion of a total area of the substrate and in which a lithography performance parameter is a characteristic associated with the substrate or with the pulsed light beam as it interacts with the substrate;

analyzing the at least one determined lithography performance parameter; and

based on the analysis of the determined lithography performance parameter:

modifying a wavelength of the pulsed light beam, wherein the modification of the wavelength causes a change in a bandwidth of the pulsed light beam, and wherein modification of the wavelength is based on a determination that the lithography performance parameter is outside an acceptable range; and

maintaining the bandwidth of the pulsed light beam to within an acceptable range of values while the wavelength is being modified.

19. The method of claim **18**, wherein maintaining the bandwidth of the pulsed light beam to within an acceptable range of values comprises adjusting the bandwidth of the pulsed light beam to compensate for the change to the bandwidth that is caused by the modification of the wavelength.

20. The method of claim **19**, wherein:

modifying the wavelength of the pulsed light beam comprises rotating a wavelength prism through which the pulsed light beam passes to change an angle of incidence between the pulse light beam and a grating; and

adjusting the bandwidth of the pulsed light beam comprises rotating a bandwidth prism through which the pulsed light beam passes by an amount that offsets a change in magnification caused by the rotation of the wavelength prism.

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